U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-257 105

Fine Shredding of Municipal Solid Waste

Midwest Research Institute

Prepared for

Environmental Protection Agency, Washington, D C Office of Research and Development

Jul 76

BEST SELLERS

FROM NATIONAL TECHNICAL INFORMATION SERVICE

NTIS

Product Liability Insurance: Assessment of Related Problems and Issues: Staff Study
PB-252 204/PAT 181 p PC$9.50/MF$3.00

Evaluation of Home Solar Heating System
UCRL-51 711/PAT 154 p PC$6.75/MF$3.00

Developing Noise Exposure Contours for General Aviation Airports
ADA-023 429/PAT 205 p PC$7.75/MF$3.00

Cooling Tower Environment, 1974. Proceedings of a Symposium Held at the University of Maryland Adult Education Center on Mar. 4-6, 1974
CONF-74 0302/PAT 648 p PC$13.60/MF$3.00

Biological Services Program. Fiscal Year 1975
PB-251 738/PAT 52 p PC$4.50/MF$3.00

An Atlas of Radiation Histopathology
TID-26-676/PAT 234 p PC$7.60/MF$3.00

Federal Funding of Civilian Research and Development. Vol. 1. Summary
PB-251 266/PAT 61 p PC$4.50/MF$3.00

Federal Funding of Civilian Research and Development. Vol. 2. Case Studies
PB-251 683/PAT 336 p PC$10.00/MF$3.00

Handbook on Aerosols
TID-26-608/PAT 141 p PC$6.00/MF$3.00

for the Assessment of Ocean Outfalls
ADA-023 514/PAT 34 p PC$4.00/MF$3.00

Guidelines for Documentation of Computer Programs and Automated Data Systems
PB-250 867/PAT 54 p PC$4.50/MF$3.00

NOx Abatement for Stationary Sources in Japan
PB-250 586/PAT 116 p PC$5.50/MF$3.00

U.S. Coal Resources and Reserves
PB-252 752/PAT 16 p PC$3.50/MF$3.00

Structured Programming Series. Vol. XI. Estimating Software Project Resource Requirements
ADA-016 416/PAT 70 p PC$4.50/MF$3.00

Assessment of a Single Family Residence Solar Heating System in a Suburban Development Setting
PB-246 141/PAT 244 p PC$8.00/MF$3.00

Technical and Economic Study of an Underground Mining, Rubblization, and In Situ Retorting System for Deep Oil Shale Deposits. Phase I Report
PB-249 344/PAT 223 p PC$7.75/MF$3.00

A Preliminary Forecast of Energy Consumption Through 1985
PB-251 445/PAT 69 p PC$4.50/MF$3.00

HOW TO ORDER

When you indicate the method of payment, please note if a purchase order is not accompanied by payment, you will be billed an addition $5.00 *ship and bill* charge. And please include the card expiration date when using American Express.

Normal delivery time takes three to five weeks. It is vital that you order by number or your order will be manually filled, insuring a delay. You can opt for *airmail delivery* for a $2.00 charge per item. Just check the *Airmail Service* box. If you're really pressed for time, call the NTIS Rush Order Service. (703) 557-4700. For a $10.00 charge per item, your order will be airmailed within 48 hours. Or, you can pick up your order in the Washington Information Center & Bookstore or at our Springfield Operations Center within 24 hours for a $6.00 per item charge.

You may also place your order by telephone or TELEX. The order desk number is (703) 557-4650 and the TELEX number is 89-9405.

Whenever a foreign sales price is NOT specified in the listings, all foreign buyers must add the following charges to each order: $2.50 for each paper copy; $1.50 for each microfiche; and $10.00 for each Published Search.

Thank you for your interest in NTIS. We appreciate your order.

METHOD OF PAYMENT

☐ Charge my NTIS deposit account no._____

☐ Purchase order no._____

☐ Check enclosed for $_____

☐ Charge to my American Express Card account number

Card expiration date_____

Signature_____

☐ Airmail Services requested

NAME_____

ADDRESS_____

CITY, STATE, ZIP_____

Item Number	Quantity		Unit Price*	Total Price*
	Paper Copy (PC)	Microfiche (MF)		
			Sub Total	
			Additional Charge	
			Enter Grand Total	

All Prices Subject to Change
11/76

Clip and mail to:

NTIS
National Technical Information Service
U.S. DEPARTMENT OF COMMERCE
Springfield, Va. 22161
(703) 557-4650 TELEX 89-9405

257093

PB 257 105

EPA-600/2-76-208
July 1976

Environmental Protection Technology Series

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-76-208		

4. TITLE AND SUBTITLE	5. REPORT DATE
Fine Shredding of Municipal Solid Waste	July 1976
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
K. P. Ananth and J. Shum	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Midwest Research Institute 425 Volker Boulevard Kansas City, Missouri 64110	EHB533
	11. CONTRACT/GRANT NO.
	68-02-1324, Task 39
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	Task Final; 6/75-6/76
	14. SPONSORING AGENCY CODE
	EPA-ORD

15. SUPPLEMENTARY NOTES Task officer for this report is J. D. Kilgroe, Mail Drop 61, Ext 2851.

16. ABSTRACT The report gives an overview of equipment used for municipal solid waste (MSW) size reduction and discusses its performance and cost. Of the 11 basic equipment types used for shredding MSW, only hammermills and grinders find wide application. An evaluation of available hammermill and grinder performance data indicates that: their specific energy consumption is independent of throughput for the same product size distributions and feed characteristics (power, however, is a function of throughput); higher shaft speeds produce finer size distributions and require more energy for the same throughputs; smaller grate spacings (exit clearances) produce finer particles; and for constant feed and shredder operating conditions, specific energy consumption is a minimum at 30-40% refuse moisture content. On the basis of available cost estimates, the initial cost for shredders ranges from $3528 to $6174 per Mg/hr. Maintenance and operating costs are estimated to be $0.77/Mg and $0.55/Mg, respectively, for shredders of 90.7 Mg/hr capacity. Fine shredding performance or cost benefits information is not available. The need for fine shredding in most material/energy recovery systems is currently dictated by process constraints and the benefits may be system specific. Generally, fine shredding is expected to enhance both energy recovery (by improving combustion efficiency) and material recovery (by increased separation effectiveness). These benefits have not been documented yet.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Fuels	Stationary Sources	21D
Wastes	Waste as Fuel	
Shredding	Municipal Solid Waste	13H, 07A

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Unlimited	Unclassified	71
	20. SECURITY CLASS (This page)	22. PRICE
	Unclassified	$4.50 - 2.25

EPA Form 2220-1 (9-73)

PRICES SUBJECT TO CHANGE

EPA-600/2-76-208
July 1976

FINE SHREDDING OF MUNICIPAL SOLID WASTE

by

K. P. Ananth and J. Shum

Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

Contract No. 68-02-1324, Task 39
Program Element No. EHB533

EPA Task Officer: James D. Kilgroe

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ACKNOWLEDGMENTS

The work presented in this report was performed for the Industrial Environmental Research Laboratory-RTP of the Environmental Protection Agency under Contract No. 68-02-1324, Task No. 39. The work was performed in the Environmental Systems Section of Midwest Research Institute. Mr. M. P. Schrag, Head, Environmental Systems Section, was the program manager and Dr. K. P. Ananth was the project leader.

Approved for:

MIDWEST RESEARCH INSTITUTE

L. J. Shannon, Assistant Director
Physical Sciences Division

30 July 1976

TABLE OF CONTENTS

		Page
List of Figures		vii
List of Tables		viii
Abstract		xi
Summary		1
Section		
I.	Introduction	4
II.	Types of Shredding Equipment	5
	Hammermills	5
	Grinders	7
	Flail Mills	10
	Manufacturer Supplied Design Data	10
III.	Shredder Performance	18
	Specific Energy Consumption	18
	Product Size Distribution	21
	Hammer Wear	30
IV.	Shredder Selection	32
V.	Shredder Costs	34
	Capital Cost	34
	Maintenance Costs	37
	Operating Cost	41
	Combined Cost	45

CONTENTS (Concluded)

Section		Page
VI.	Evaluation of Material/Energy Recovery Systems.	49
	Pyrolysis Systems.	49
	Combined Firing Systems.	52
	Summary.	53
VII.	Conclusions and Recommendations	54
References.		56

LIST OF FIGURES

Figure	Title	Page
1	Horizontal Shaft Hammermill	6
2	Vertical Shaft Hammermill (Heil Company).	8
3	Cross-Section of the Eidal Grinder.	9
4	Average Power Versus Dry Feed Rate for Primary and Secondary Grinding.	19
5	Characteristic Particle Size Versus Specific Energy Consumption	22
6	Size Distribution of Refuse From Various Shredders. . .	24
7	Effect of Grate Size on Particle Size Distribution at Madison	25
8	Characteristic Particle Size Versus Grate Spacing . . .	27
9	Effect of Moisture Content on Particle Size Distribution.	28
10	Effect of Moisture Content on Particle Size Distribution.	28
11	Changes in Particle Size Distribution Due to Cumulative Hammer Wear.	29
12	Power Requirement as a Function of Feed Rate and Characteristic Particle Size Desired.	33
13	Estimated Operating Cost for Various Shredder Capacities.	46
14	Total Cost Versus Rated Capacity.	48

LIST OF TABLES

Table	Title	Page
1	Advantages and Disadvantages of Some Shredder Types Based on Various Criteria	11
2	1975 Survey of Shredders Used (or to be used) for Size Reduction of MSW in the United States	12
3	Design Specifications for Typical Horizontal Type Shredders Used for Processing MSW	16
4	Design Specifications for Typical Vertical Type Shredders Used for Processing MSW	17
5	Product Size Distributions at St. Louis Plant During Test Period 9/30/74 - 11/18/74.	23
6	Production and Power Use at St. Louis Shredder During Test Period 9/30/74 - 11/18/74.	23
7	Average Wear for Hammers and Grate Bars Under Different Speeds and Hammer Facing Conditions	31
8	Initial Cost for Shredders of Various Capacities. . . .	35
9	Initial Cost for Shredders of Equivalent Size	36
10	Estimated Annualized Capital Cost	38
11	Comparison of Unit Costs for Madison and Gainesville Plants.	39

TABLES (Concluded)

Table	Title	Page
12	Maintenance Cost for Various Components of Two Shredder Units	40
13	Maintenance Cost for (45 Mg/hr) Shredder Units as Provided by Manufacturers	42
14	Maintenance Costs Observed at Madison and Gainesville	43
15	Estimated Operating Cost for Primary Shredder Units	44
16	Combined Cost of Shredding MSW	47
17	Pyrolysis and Combined Firing Systems Investigated to Determine the Benefits of Fine Shredding	49
18	Size Distribution of Garrett Secondary Shredded Solid Waste	51
19	Typical Size Distribution of Shredded, Air Classified Refuse in St. Louis	52

ABSTRACT

This report presents an overview of equipment used for municipal solid waste (MSW) size reduction and discusses their performance and cost aspects. Of the 11 basic types of equipment used for shredding MSW, only hammermills and grinders find wide application. Evaluation of their performance on the basis of specific energy consumption as a function of various factors such as throughput, shaft speed, grate spacings, refuse moisture content, etc., indicates that:

- The specific energy consumption is independent of throughput for the same product size distributions and feed characteristics. The power, however, is a function of throughput.
- Higher shaft speeds (rpm) produce finer size distributions and require more energy for the same throughputs.
- Smaller grate spacings (exit clearances) produce finer particles.
- Refuse moisture content has a definite effect on specific energy consumption. The relationship is parabolic with increasing moisture content, first reducing specific energy consumption and then increasing it. The specific energy consumption is a minimum at 35 to 40% moisture content.

On the basis of available cost estimates, the initial cost for shredders ranges from $3,528 to $6,174/Mg/hr or $3,200 to $5,600/ton/hr. The annualized capital cost is about $0.21/Mg or $0.19/ton. Maintenance and operating costs are estimated to be $0.33 and $1.74/Mg, respectively, for a shredder of capacity 9.07 Mg/hr (i.e., 10 tons/hr). For a shredder of 90.7 Mg/hr capacity, maintenance and operating costs are estimated to be $0.77 and $0.55/Mg, respectively.

Information on performance or cost benefits of fine shredding is currently lacking. The need for fine shredding in most material/energy recovery systems is currently dictated by process constraints and the benefits may be system specific. On a general basis, fine shredding is expected to enhance

energy recovery by improving combustion efficiency and to enhance material recovery due to increased effectiveness of separation devices. These benefits have not been documented as yet.

SUMMARY

The Environmental Protection Agency (EPA) is supporting development of processes for recovery of material and energy from municipal solid wastes (MSW). To accomplish this goal, information is required on performance and cost of MSW size reduction equipment since they are critical for optimization of resource recovery systems.

The objective of this task was to (a) develop a technology overview of equipment used for municipal solid waste size reduction, (b) develop performance and cost data on MSW size reduction equipment, and (c) evaluate performance/cost benefits from shredding* refuse to finer levels in selected resource recovery systems.

In conducting this task, Midwest Research Institute (MRI) reviewed existing literature and contacted: (a) manufacturers of equipment for size reduction of municipal solid waste; (b) the Shredder Subcommittee of the Waste Equipment Manufacturer's Institute of the National Solid Waste Management Association; (c) engineering consultants with expertise in this field; and (d) users of MSW size reduction equipment.

Equipment used for size reduction of MSW can be categorized into 11 basic types. Of these, only hammermills and grinders are extensively used and only these two are discussed in any detail in this report. Variations in the design and operation of these equipment and their advantages and disadvantages are also presented.

The performance of shredders is discussed based upon their specific energy consumption (kw-hr/Mg), product size distribution, and frequency of replacements needed or machine wear. These performance parameters are dependent upon factors such as throughput, grate spacings, motor shaft speed (rpm), feed moisture content, feed size distribution, and feed composition. Pertinent observations include:

---

* Waste Equipment Manufacturer's Institute has designated the term "Shredder" to cover all mechanical equipment used to break up solid waste and recoverable materials to smaller sizes. MRI has also used this designation throughout this report.

- The specific energy consumption appears independent of throughput for the same product size distributions and feed characteristics. The power, however, is a function of throughput.

- Higher shaft speeds (rpm) produce finer size distributions and require more energy for the same throughputs.

- Smaller grate spacings (exit clearances) produce finer particles.

- Refuse moisture content has a definite effect on specific energy consumption. The relationship is parabolic with increasing moisture content, first reducing specific energy consumption and then increasing it. The specific energy consumption is a minimum at 35 to 40% moisture content.

- The effect of refuse moisture content on product size distribution could not be determined because of the lack of data on this subject.

- Increased hammer wear results in a coarser product.

Cost data on shredders are scarce and even the limited information varies from one manufacturer to another. Also, some cost quotations include accessories and others do not. However, best estimates indicate that the initial cost for shredders, with comparable accessories, ranges from $3,528 to $6,174/Mg/hr ($3,200 to $5,600/ton/hr). With an assumed initial cost of $4,410/Mg/hr ($4,000/ton/hr) and 1,820 annual operating hours, the annualized capital cost based on refuse processed annually is $0.21/Mg when the equipment is amortized for 20 years at zero salvage value and 6% interest rate. The corresponding cost per ton is $0.19. This cost is independent of the equipment's rated capacity. Maintenance and operating cost information are available in the literature, but due to differences in cost accounting practices much of the data are not amenable for direct comparison. Based on best engineering judgment and conversations with knowledgeable persons in the shredding field, the maintenance and operating costs were estimated to be about $0.33 and $1.74/Mg, respectively, for a 9.07 Mg/hr capacity;* for a capacity of 90.7 Mg/hr, they were about $0.77/Mg for maintenance costs and $0.55/Mg for operating costs. It appears that maintenance costs increase with unit size but we have not been able to establish the reasons for this relationship due to lack of data.

Material/energy recovery systems such as pyrolysis and combined firing (coal-refuse) were evaluated to determine if cost or performance benefits may be derived from shredding refuse to finer levels. It appears that

* A capacity of 9.07 Mg/hr corresponds to 10 tons/hr.

process constraints, more than anything else, dictate the need for shredding and the major benefit, as such, may be from an increase in the combustion/reaction efficiency. The Occidental Petroleum Company, Monsanto Corporation, and the Union Carbide Corporation all shred the refuse prior to using it in their pyrolysis systems, but they have not been able to provide us any information on cost or performance benefits. The St. Louis demonstration project which fires coal and refuse in a utility boiler also shreds the refuse and classifies it prior to feeding it into the boiler. No quantitative data are reported on the benefits of fine shredding the refuse.

SECTION I

INTRODUCTION

Material and/or energy recovery processes from municipal solid waste have grown in importance recently due to (a) the search for new energy sources, (b) increased concern in the location and presence of landfills, and (c) the possibility of recovering nonrenewable mineral resources. Intrinsic to these processes is the need for size reduction of MSW.

At present there is little published information on the cost and performance of equipment for MSW size reduction. This project was undertaken to provide an overview of the technology behind shredders and to develop cost and performance data. Also included in the project was the evaluation of existing material/energy recovery systems to determine the cost/performance benefits of fine shredding.

A literature search was first undertaken to identify gaps in the data base. In addition, shredder manufacturers, the National Solid Waste Management Association, users of MSW size reduction equipment and engineering consultants with expertise in this field were contacted. The technology overview is presented in the next section. This is followed by sections on performance, costs, and evaluation of existing material/energy recovery systems. Conclusions and recommendations based on this study are also presented.

SECTION II

TYPES OF SHREDDING EQUIPMENT

Size reduction or shredding of municipal solid waste is the mechanical process of breaking up solid waste and recoverable materials to smaller sizes. There are, at present, 11 basic types of shredding equipment which are commercially available. These are: crushers, cage disintegrators, shears, grinders, cutters and chippers, rasp mills, drum pulverizers, disk mills, wet pulpers, hammermills, and flail mills.[1,2] Of these, only hammermills and grinders have been used widely in the United States for the size reduction of MSW.[2] Therefore, this discussion will be devoted mainly to these two types of shredders. A brief description of the flail mill is also included at the end, since it is a new concept.[3]

HAMMERMILLS

Hammermills are currently the most popular type of shredder equipment used for MSW size reduction. A hammermill consists of a radial rotor or shaft with hammers attached to the rotor by means of the hammer pins. These pins are long rods which, in effect, lace the hammers to the rotor by running them through the holes in the rotor and hammers. When the entire assembly is rotating, the hammers fly perpendicular to the rotor. The moving parts are enclosed in a heavy duty housing which may be lined with abrasion resistant steel structures. Input materials are shredded by impact, attrition and shearing forces induced by the hammers. Sometimes stationary breaker plates or cutter bars are placed inside the housing to assist shredding.

There are two basic types of hammermills. These are the horizontal shaft type and the vertical shaft type. The horizontal shaft hammermill has the shaft or rotor mounted horizontally and supported on each end. The rotors can be designed to rotate in either direction. Input solid waste is generally fed from the top assisted by gravity and the rotor torque. Force feed at the side of the hammermill has also been used. A schematic diagram of a horizontal hammermill is shown in Figure 1.

The hammers attached to the rotor are either of swinging or rigid type. The swinging hammers are mounted on pins and are free to rotate.

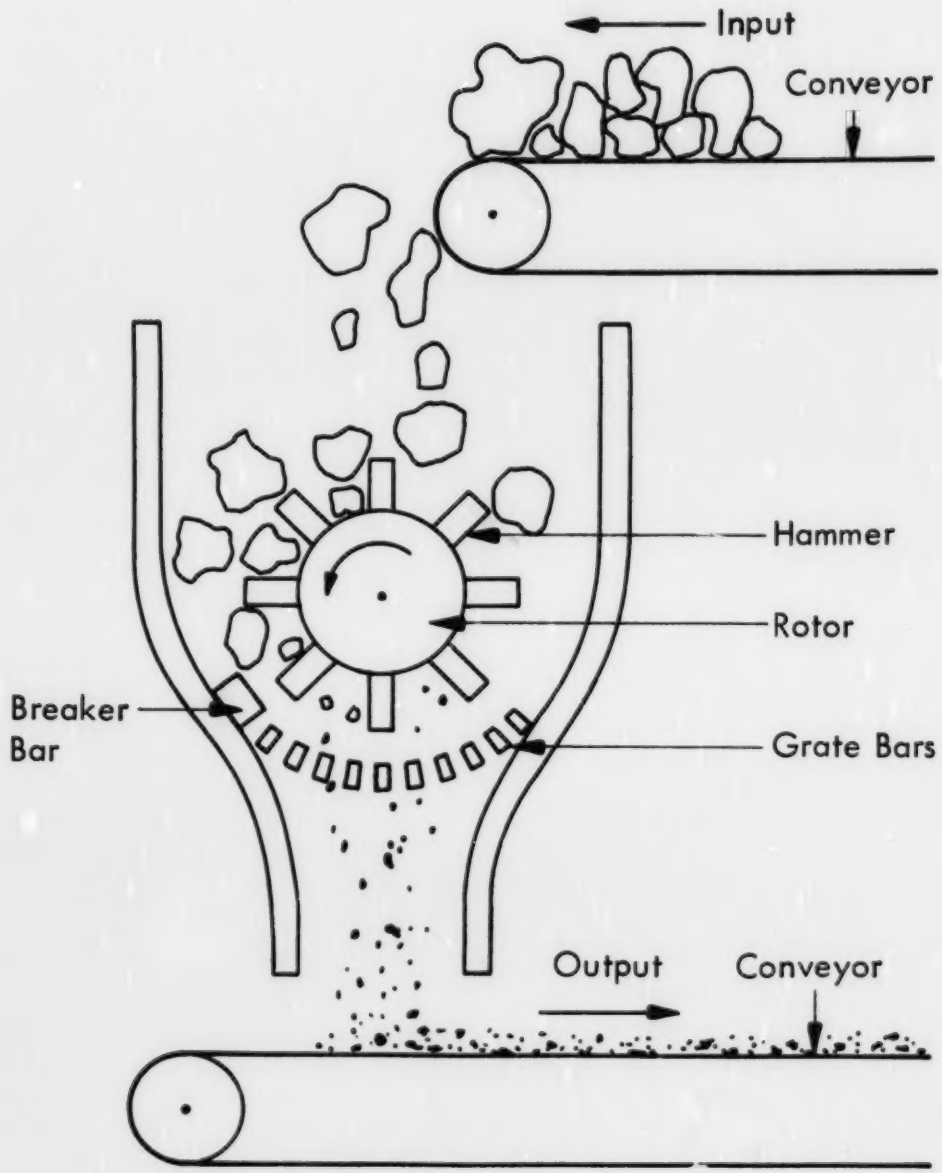


Figure 1. Horizontal shaft hammermill.

This design reduces hammer damage. However, when the hammers become entangled with the input material and are not allowed to swing freely, severe imbalance problems can arise. For both types of hammers, shapes vary from sharp choppers to blunt rectangular beaters. The latter are most often used for solid waste size reduction.

Output material size in a horizontal type hammermill is controlled by the size of the openings of the grate. The grate is located across the output opening of the hammermill. Input material remains in the hammermill until it is small enough in at least two dimensions to fall through the grate openings.

Most manufacturers of horizontal shaft hammermills recommend direct coupling of the motor and the shredder rotor shafts. This procedure is generally the simplest and least expensive connection method.

The vertical shaft hammermill has the rotor placed in a vertical position. Input material enters at the top and progresses downward parallel to the shaft axis. Both types of hammer design (swinging or rigid) have been used with the vertical hammermill. A typical vertical shaft hammermill is shown in Figure 2.

The vertical shaft hammermill has no grate system at the discharge section of the machine. Particle size control is effected by the decreasing clearance between the hammer tips and the housing from top to bottom. However, output particle size increases as hammers and housing plates wear.

Direct coupling of the motor shaft to the vertical shaft is not practical. Generally a gear or belt drive system is used. While the belt drive permits some flexibility in motor location, the gear drive normally requires additional support equipment and thus increases maintenance requirements.

GRINDERS

Another common type of equipment used for size reduction of MSW is the vertical shaft grinder. Figure 3 illustrates a typical vertical grinder. The principle adopted in the design of such a grinder differs from that of the hammermill in that size reduction is accomplished by a set of gearlike teeth installed in a rotor which fits in a stationary ribbed housing. The input material introduced into the upper part of the machine is first exposed to a set of breaker bars by means of which large objects are torn apart. The material then enters the space between the rotor teeth and the housing ribs. Size reduction occurs in this part of the machine due to the

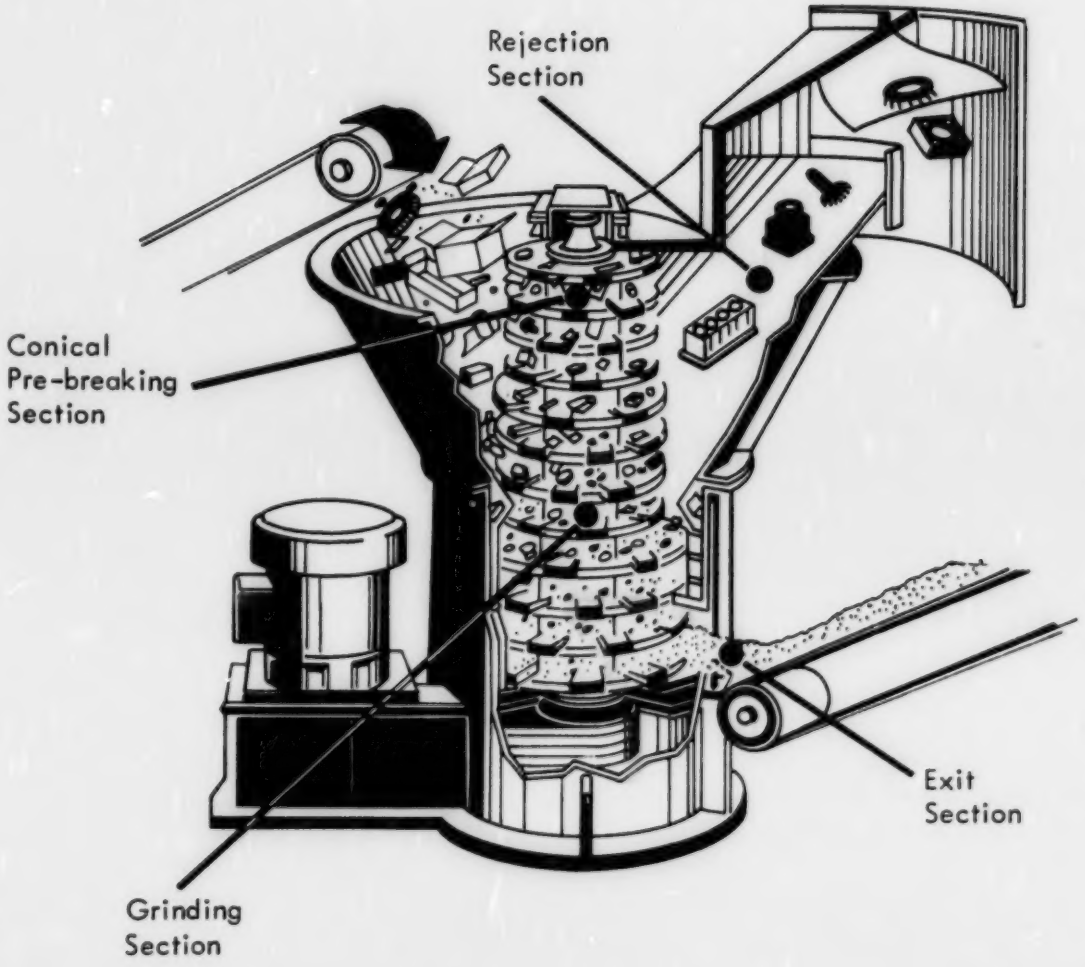


Figure 2. Vertical shaft hammermill (Heil Company).

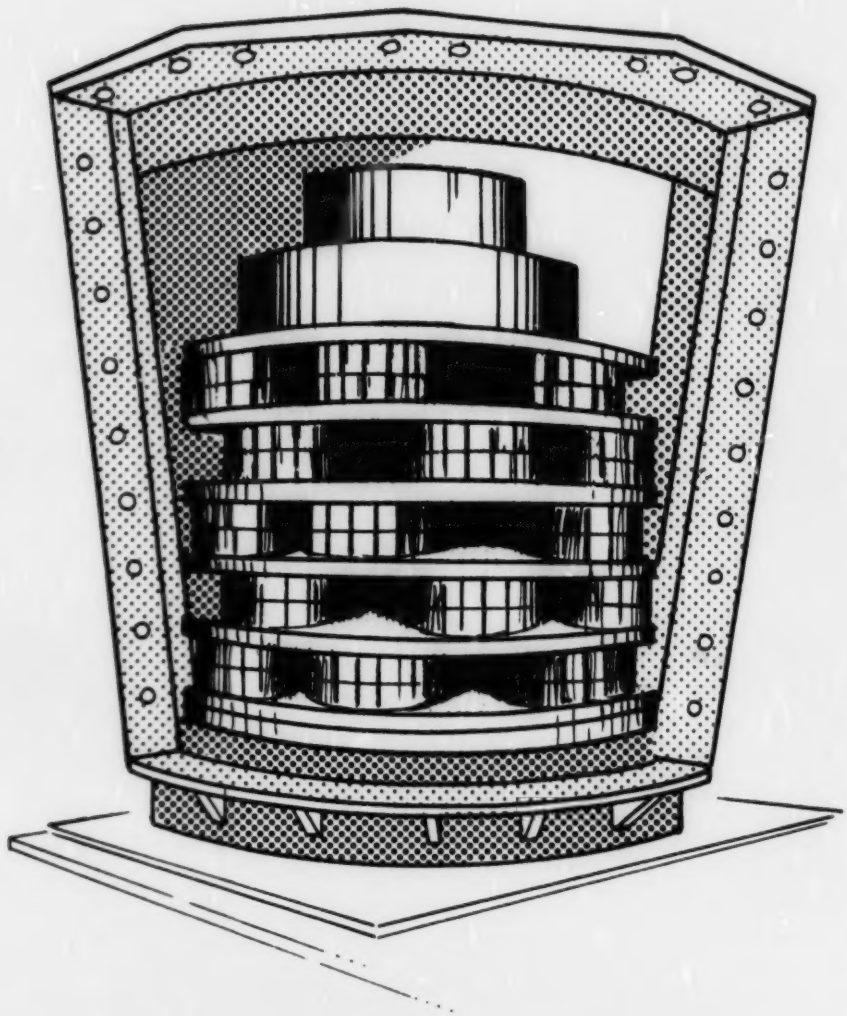


Figure 3. Cross-section of the Eidal grinder.

induced shear and the mutual self-comminution interaction between the various types of materials.[4]

The space between the rotor and the housing is tapered and this decreasing clearance geometry controls the size of the product leaving the grinder. The main advantages of the grinder are its low speed (~ 400 rpm) and no objects are rejected as in a hammermill.

FLAIL MILLS

A third type of shredder which has recently been applied to MSW is the flail mill. The shredding is done using articulated flails mounted on opposed rotors. Since a flail mill passes all input materials quickly without repeated impacts, energy and cost requirements are much lower than in conventional shredders where solid waste is ground or forced through a grate system. A power consumption of 5.1 kw-hr/Mg (6.2 HP-hr/ton) of refuse has been reported by one manufacturer.[5] Another advantage of the flail mill is that it can operate at maximum capacity without large variations in load due to a more uniform impacting situation.[5] Flail mills have been used as primary shredders in solid fuel and pyrolysis process systems developed by Combustion Equipment Associates, Inc., and Arthur D. Little, Inc.[3,6]

Table 1 summarizes the advantages and disadvantages of the shredders discussed above and Table 2 presents a listing of shredding facilities which are now in operation, or for which ground has been broken throughout the United States.[7] Table 2 includes shredder type and also the rated capacity. The original list[7] has been modified to indicate only those shredder systems which shred MSW for energy and/or resource recovery.

MANUFACTURER SUPPLIED DESIGN DATA

Several manufacturers of shredders were contacted to obtain design specifications for their systems. Most of them responded with company brochures and provided additional information. Design data for some systems had to be obtained from the open literature. Tables 3 and 4 are listings of design specifications that were available to us. The data are grouped by shredder type (horizontal or vertical) and by rated capacity.

Table 1. ADVANTAGES AND DISADVANTAGES OF SOME SHREDDER TYPES BASED ON VARIOUS CRITERIA

	Horizontal hammermills	Vertical hammermills	Grinders	Flail mills
Application	Wide range	Wide range	Wide range	Principally limited to primary stage size reduction
Handling of hard objects	Difficult and causes jamming	Rejected ballistically or passed through without much size reduction	Not rejected	Passed through without much size reduction
Particle size (product) control	Can be well controlled by adjusting grates	Less uniformity in particle size distribution	Can be well controlled	Moderately uniform
Wear rate	High	Low	Low	Low
Power requirement	High	Lower than horizontal hammermills	High	Low
Auxiliary equipment needed	None, if direct driven	Requires gear or belt drive to couple with motor	Requires gear or belt drive to couple with motor	None

Table 2. 1975 SURVEY OF SHREDDERS USED (OR TO BE USED) FOR SIZE REDUCTION OF MSW IN THE UNITED STATES

Location	Start-up date	Type of shredder	Type of shredder waste	Rated capacity	Disposition of waste
California					
Los Gatos	1969	Horizontal shaft 3 units - primary, secondary, tertiary	Municipal, both packer truck and bulky waste	27 Mg/hr (30 tons/hr) for whole system	Recycling and energy recovery
Menlo Park	March 1973	Vertical	Municipal and packer truck	2.7 Mg/hr (3 tons/hr)	Power generation
San Diego	March 1976	Horizontal hammermill	Municipal	32 Mg/hr (35 tons/hr)	Pyrolysis
Connecticut					
Bridgeport	August 1976	2 horizontal hammermills	Municipal	68 Mg/hr (75 tons/hr) each	Generate electricity
Florida					
Ft. Lauderdale	1973	Horizontal	Municipal	366 m/hr (400 yd/hr)	Incineration/ landfill
Illinois					
Chicago	1971	Horizontal	Municipal	27 Mg/hr (30 tons/hr)	Incineration

Table 2. (Continued)

Location	Start up date	Type of shredder	Type of shredder waste	Rated capacity	Disposition of waste
Illinois (Concluded)					
Chicago	1975	2 vertical	Secondary grind	54 Mg/hr (60 tons/hr) each	Fuel supplement
Chicago	June 1975	Vertical	Secondary grind	54 Mg/hr (60 tons/hr)	Energy recovery
Chicago	October 1975	Horizontal	Municipal and oversized bulky waste	68 Mg/hr (75 tons/hr)	Btu recovery
Iowa					
Ames	June 1975	2 horizontal hammermills	Municipal	45 Mg/hr (50 tons/hr)	Generate electricity
Pleasant Hill	1973	Horizontal, single direction	Municipal	18 Mg/hr (20 tons/hr)	Composting and pyrolysis
Maryland					
Baltimore	1974	2 horizontal	Municipal, industrial oversized bulky	45 Mg/hr (50 tons/hr) each	Pyrolysis
Massachusetts					
Marlboro	November 1973	Horizontal	Municipal	27 Mg/hr (30 tons/hr)	Incineration

Table 2. (Continued)

Location	Start up date	Type of shredder	Type of shredder waste	Rated capacity	Disposition of waste
Missouri					
St. Louis	1971	Horizontal	Municipal	68 Mg/hr (75 tons/hr)	Power generation
St. Louis	April-December 1976	7 horizontal primaries	Packer and oversized bulky waste	91 Mg/hr (100 tons/hr) each	Energy recovery and ferrous recovery
St. Louis	April-December 1976	7 horizontal secondaries	Primary shedded materials ferrous removed	86 Mg/hr (95 tons/hr) each	Energy recovery
New York					
Buffalo	1970	Horizontal	Municipal	184 cu m/hr (240 cu yd/hr)	Incineration
Pennsylvania					
Harrisburg	December 1970	Horizontal	Municipal	73 Mg/hr (80 tons/hr)	Incineration
York	1975	Horizontal	Municipal, packer truck	23 Mg/hr (25 tons/hr)	Incineration

Table 2. (Concluded)

Location	Start up date	Type of shredder	Type of shredder waste	Rated capacity	Disposition of waste
Washington					
Cowlitz County	1975	Horizontal	Municipal	45 Mg/hr (50 tons/hr)	Power generation
Longview	1971	Horizontal	Municipal and pulp and paper mill waste	45 Mg/hr (50 tons/hr)	In plant incineration
West Virginia					
South Charleston	1975	Vertical	Municipal	14 Mg/hr (15 tons/hr)	Pyrolysis
Wisconsin					
Milwaukee	August 1976	2 horizontal primaries	Packer and oversized bulky waste	73 Mg/hr (80 tons/hr) each	Energy recovery and ferrous separation

Table 3. DESIGN SPECIFICATIONS FOR TYPICAL HORIZONTAL TYPE SHREDDERS USED FOR PROCESSING MSW

Capacity (Mg/hr)	Capacity (tons/hr)	Manufacturer	Model No.	Power (kw)	Power (HP)	Speed (rpm)	Feed opening (cm)	Feed opening (in.)	Dimensions (cm)a/ Length	Dimensions (cm)a/ Width	Dimensions (cm)a/ Height	Weight (kg)	Weight (lb)	Reference
0.9-1.8	1-2	Pennsylvania Crusher Corporation	S12024	19	25		41 x 64	16 x 25				816	1,800	1
1.8-4.5	2-5	Pennsylvania Crusher Corporation	S13030	45	60		64 x 89	25 x 35				2,720	6,000	1
4.5-9.1	5-10	Pennsylvania Crusher Corporation	S13640	93	125		74 x 112	29 x 44				3,630	8,000	1
6.3	7	Jeffrey Manufacturing Company	432	75	100		81	32						1
7.3	8	Goodard Mill		112	150	1,150								10
9.1	10	American Pulverizer Company	4200				79 x 140	31 x 55	183 (72)	239 (94)	134 (49)	8,620	19,000	Company bulletin
9.1	10	Gruendler Crusher and Pulverizer Company	48-4	186	250	1,200								11
9.1-14	10-15	Pennsylvania Crusher Corporation	SH3640	149	200		64 x 102	25 x 40				6,120	13,500	1
14	15	Jeffrey Manufacturing Company	548	186	250		122	48						1
14-18	15-20	Pennsylvania Crusher Corporation	SH3666	224	300		64 x 152	25 x 60				5,670	12,500	1
18	20	American Pulverizer Company	48-50	298-373	400-500	900	127 x 137	50 x 54	259 (102)	297 (117)	185 (73)	18,100	40,000	Company bulletin, private communication
18	20	Williams Hammermills	GA-70	298	400	1,200	61 x 178	24 x 70				8,940	19,700	19
18-27	20-30	Pennsylvania Crusher Corporation	SH4454	298	400		81 x 142	32 x 56				9,070	20,000	1
22	24	Hammermills, Inc.	4260	447	600									
23	25	Jeffrey Manufacturing Company	748	298	400		122	48						Company bulletin 1
27	30	American Pulverizer Company	60-50	522-746	700-1,000	900	122 x 132	48 x 52	262 (103)	305 (120)	229 (90)	28,600	63,000	Company bulletin, private communication
27	30	Williams Hammermills	K-460	298	400	800	142 x 160	56 x 63				15,200	33,500	19
27-36	30-40	Pennsylvania Crusher Corporation	SH6478	447	600		81 x 203	32 x 80				12,700	28,000	1
29	32	Hammermills, Inc.	6060	597	800									
32	35	Jeffrey Manufacturing Company	770	373	500		178	70						Company bulletin 1
36	40	Hammermills, Inc.	6080	746	1,000									
36-45	40-50	Pennsylvania Crusher Corporation	SH5484	597	800		107 x 213	42 x 84				21,800	48,000	Company bulletin 1
45	50	American Pulverizer Company	60-90	746	1,000	720	122 x 234	48 x 92	262 (103)	406 (160)	229 (90)	47,600	105,000	Company bulletin, 6
45	50	Gruendler Crusher and Pulverizer Company	60x84	932	1,250	894								14
50	55	Jeffrey Manufacturing Company	990	559	750		229	90						1
73	80	Hammermills, Inc.	74104	1,490	2,000									
91	100	American Pulverizer Company	72-72	1,120-1,490	1,500-2,000	900	173 x 193	68 x 76	343 (135)	462 (182)	312 (123)	86,200	190,000	Company bulletin Company bulletin, private communication
91	100	American Pulverizer Company	72-84	1,120-1,490	1,500-2,000	900	173 x 224	68 x 88	343 (135)	493 (194)	312 (123)	95,300	210,000	Company bulletin, private communication
109	120	Hammermills, Inc.	96104	2,240	3,000									Company bulletin
136	150	American Pulverizer Company	96-90	2,240-3,730	3,000-5,000	720	213 x 234	84 x 92	437 (172)	503 (198)	371 (146)	134,000	925,000	Company bulletin, private communication

a/ Except numbers in parenthesis, which are in inches.

Table 4. DESIGN SPECIFICATIONS FOR TYPICAL VERTICAL TYPE SHREDDERS USED FOR PROCESSING MSW

Capacity (Mg/hr)	Capacity (tons/hr)	Manufacturer	Model No.	Power (kw)	Power (HP)	Speed (rpm)	Feed opening (cm)	Feed opening (in.)	Weight (kg)	Weight (lb)	Reference
0.9-3.6	1-4	The Carborundum Company	100	75	100	415	132 x 76	52 x 30	6,100	13,450	Company bulletin, 1
14	15	The Heil Company	42-D	149	200		76 x 122	30 x 48			Private communication, 1
14	15	Tollemache Mill		149	200	1,300					10
14-32	15-35	The Carborundum Company	400	298[a]	400[a]	390	152 x 152	60 x 60	17,200	38,000	Company bulletin, 1
18	20	The Heil Company	42-F	186	250		107 x 152	42 x 60			Private communication, 1
27-50	30-55	The Carborundum Company	1000	746[b]	1,000[b]	369	152 x 224	60 x 88	4,170	92,000	Company bulletin, 1
36-41	40-45	The Heil Company	72	373	500						Private communication
45	50	The Heil Company	92	373	500		122 x 213	48 x 84			Private communication, 1
54	60	The Heil Company	92	559	750		122 x 213	48 x 84			Private communication, 1
68	75	The Heil Company	92	746	1,000		122 x 213	48 x 84			Private communication, 1
73-91	80-100	The Heil Company	92	746	1,000						Private communication

a/ Uses two 149 kw (200 HP) motors.
b/ Uses two 373 kw (500 HP) motors.

SECTION III

SHREDDER PERFORMANCE

Performance data for some shredder units have been reported by Ruf,[8] Gawalpanchi et al.,[9] and Reinhardt et al.[10] A more systematic investigation of shredder performance and the effect of various parameters on performance has been recently reported by Trezek et al.[11,12] Trezek's study[12] was conducted with a Gruendler-Model 48-4 hammermill with a design capacity of up to 9.1 Mg/hr (10 tons/hr). The effects of feed rate, grate or extraction spacing and hammer speed (rpm) on product size distribution and specific energy consumption were investigated under controlled laboratory conditions. Also, particle size distributions of shredder refuse from different types of shredders are reported.[12] A mathematical simulation of the comminution process in a swing hammermill using four matrix models is also available.[13] The models can be used to predict product size distributions for primary, secondary, and tertiary grinding processes. The difficulty, however, is to obtain selection and breakage functions for the models from first principles.

Our evaluation of shredder performance is based on information contained in Refs. 11 and 12 and data obtained from field studies in Gainesville,[8] Madison,[9,10] and St. Louis.[14] We have characterized shredder performance in terms of specific energy consumption, product size distribution, and machine wear or frequency of replacements required. Factors such as feed throughput, shredder/hammer design, rotor speed (rpm), feed moisture content, feed size distribution and feed composition, which affect shredder performance are also discussed.

SPECIFIC ENERGY CONSUMPTION

Factors which can affect the specific energy consumption (kw-hr/Mg) are shredder/hammer design, rotor speed, and feed moisture content, feed size distribution, and feed composition. As shown in Figure 4, feed throughput has minimal effect on specific energy consumption for both primary and secondary grinding except at very low feed rates such as those below 1.8 Mg/hr (2 tons/hr).[11] At feed rates below 1.8 Mg/hr (2 tons/hr) the specific energy consumption is not a constant.[11] In Figure 4, the output from primary grinding was used as the feed for secondary grinding. No size data were reported.

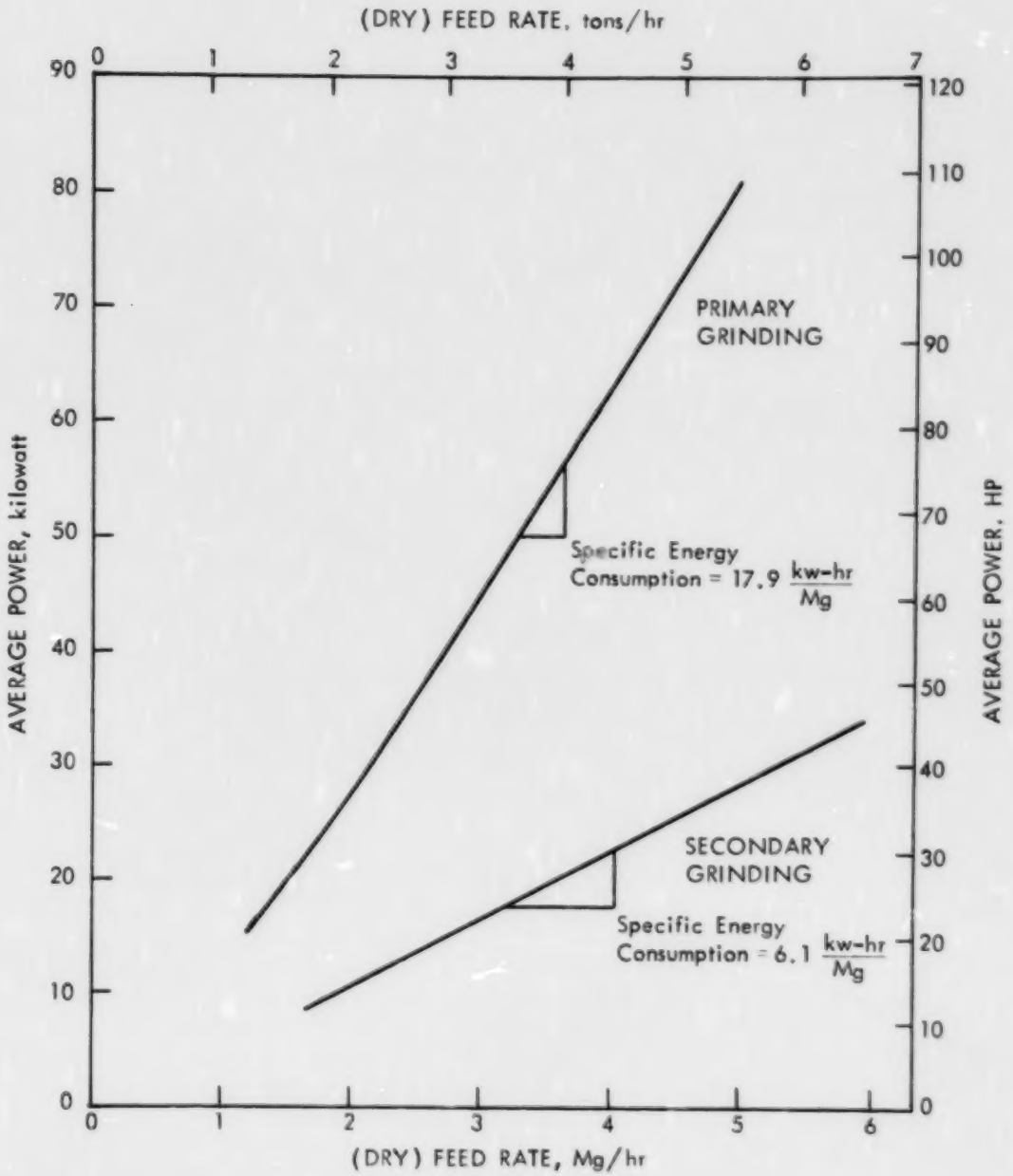


Figure 4. Average power versus dry feed rate for primary and secondary grinding.[11]

The type of shredder used can alter the specific energy consumption. For instance, horizontal-shaft hammermills generally require more energy since particles must be ground fine enough to pass through the grate openings. The Madison study[9,10] shows that the Gondard mill (i.e., horizontal shaft) has a specific energy consumption of 13.8 kw-hr/Mg (16.8 HP-hr/ton) whereas the Tollemache mill (i.e., vertical shaft) only needs 7.9 kw-hr/Mg (9.7 HP-hr/ton). The machines used in the above study were of comparable size and were operated under comparable conditions. The use of a flail mill results in a more drastic reduction in the specific energy consumption. A value of 5.1 kw-hr/Mg (6.2 HP-hr/ton) is reported for a flail mill.[5]

Experience with the Tollemache mill at Madison indicates that the number of hammers, their size and arrangement can affect specific energy consumption. The original design of 54 hammers when replaced with 34 hammers arranged in a more efficient manner actually increased production at Madison, resulting in a decrease in specific energy consumption.[10]

For constant feed throughputs and feed conditions, any increase in rotor speed will increase the specific energy consumption. It is reported[12] that an increase in speed from 790 to 1,200 rpm at a feed rate of 4.5 Mg/hr (5 tons/hr) raises the specific energy consumption from about 11.0 to 18.7 kw-hr/Mg (13.4 to 22.8 HP-hr/ton) on a dry basis. No additional data are available to determine the exact relationship. Higher speeds, however, have the benefit of generating finer particles as will be shown in the next section.

Variations in feed size distribution and feed composition will influence specific energy consumption. Larger particles and a larger percentage of high tensile strength materials in the feed stream could increase the specific energy consumption. For example, a secondary shredder which is preceded by a magnetic separator and an air classifier after the primary unit should consume less energy than one without these systems before it. At the present time there are no data to document this expectation.

Trezek's study[12] and the Madison study[10] both report the influence of refuse moisture content on the specific energy consumption. Trezek[12] indicates that for a horizontal shredder the specific energy consumption generally decreases with increasing moisture content up to a certain point and then increases with moisture content beyond that point. Typically, minimum energy consumption is observed between 35 and 40% moisture. The Madison study showed that for a vertical Tollemache hammermill, the winter refuse having 24% moisture required 12.0 kw-hr/Mg (14.6 HP-hr/ton) in contrast to the summer refuse with 36% moisture which required only 9.7 kw-hr/Mg (11.8 HP-hr/ton). The effect of higher moisture contents (> 36%) on

specific energy consumption are not reported in the Madison study. Therefore, no comparisons can be made between Refs. 10 and 12 for moisture contents greater than 36%.

The specific energy consumption is also a function of product size, and was found to be related to a characteristic particle size, x_o, which corresponds to a 63.2% cumulative passing in a Rosin-Rammler distribution of the form:[12]

$$y(x) = 1 - \exp\left[-\left(\frac{x}{x_o}\right)^n\right]$$

In the above equation, $y(x)$ is the cumulative percent passing screen size x and n is the slope of the line $\ln[1/(1-y)]$ versus x on log-log coordinates. The relationship between characteristic particle size, x_o, and specific energy consumption is illustrated in Ref. 12 and is shown in Figure 5. In the same figure we have also shown the range of characteristic particle sizes, x_o, and the range of specific energies consumed to produce those sizes in the St. Louis study.[14] Tables 5 and 6 were used to establish the St. Louis range of characteristic particle sizes and the range of specific energies, respectively. It can be seen from Figure 5 that, for a characteritic size range of 1.2 to 1.4 cm (i.e., values observed in St. Louis), the specific energy consumption should lie between 21.8 and 23.8 kw-hr/Mg (26.6 and 29.0 HP-hr/ton) according to the relationship established by Trezek.[12] The actual energy values observed at St. Louis for this particle size range lie between 21.1 and 23.5 kw-hr/Mg (25.6 and 28.7 HP-hr/ton) (see Table 6). The individual points obtained in St. Louis are also plotted in the figure showing good agreement between values predicted by theory and those actually observed.

PRODUCT SIZE DISTRIBUTION

The size distribution of shredded refuse from various grinders is shown in Figure 6. However, these distribution curves cannot be compared since they can be affected by grate spacing, feed characteristics, rotor speed and hammer wear and these differences in operating conditions are not well identified. Variation in feed rate has only a minor effect on product size distribution.[11]

The grate spacings of the Gondard hammermill (7.3 Mg/hr or 8 tons/hr) at Madison were varied from 8.9 to 15.9 cm (3-1/2 to 6-1/4 in.) and the product size was determined. Figure 7 shows the product size distributions obtained for the various grate spacings.[15]

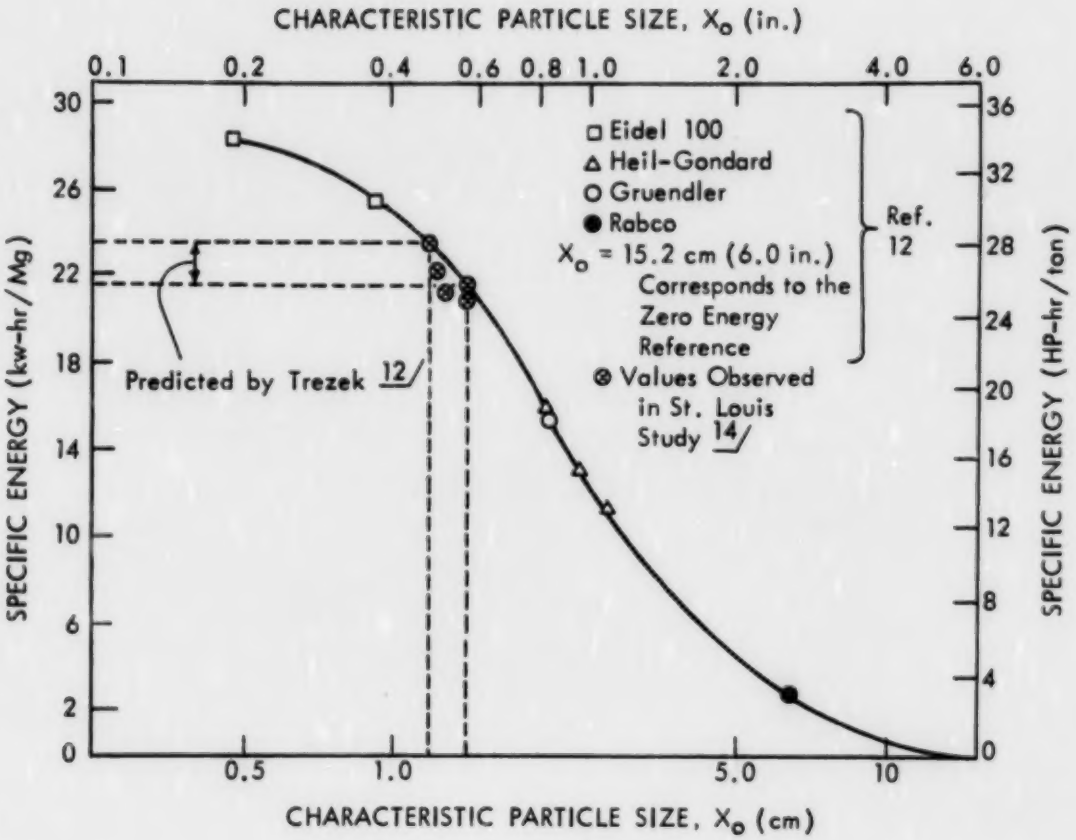


Figure 5. Characteristic particle size versus specific energy consumption.12/

Table 5. PRODUCT SIZE DISTRIBUTIONS AT ST. LOUIS PLANT DURING TEST PERIOD 9/30/74 - 11/18/74[14]

	Week of				
	9-30	10-7	10-14	10-21	11-18
% larger than 6.4 cm (2.5 in.)	0	0.6	0	0	0
% less than 6.4 cm (2.5 in.)	100.0	99.4	100.0	100.0	100.0
% less than 3.8 cm (1.5 in.)	97.0	96.4	98.1	97.4	97.2
% less than 1.9 cm (0.75 in.)	72.1	71.6	78.0	72.8	70.0
% less than 0.95 cm (0.375 in.)	45.1	45.8	54.2	47.1	42.3
% less than 0.47 cm (0.187 in.)	23.7	28.2	33.1	30.3	24.3
% less than 0.24 cm (0.094 in.)	11.6	18.1	20.0	16.1	17.0
Characteristic size x_o (cm)[a]	1.4 (0.56)	1.3 (0.52)	1.2 (0.48)	1.3 (0.50)	1.4 (0.56)

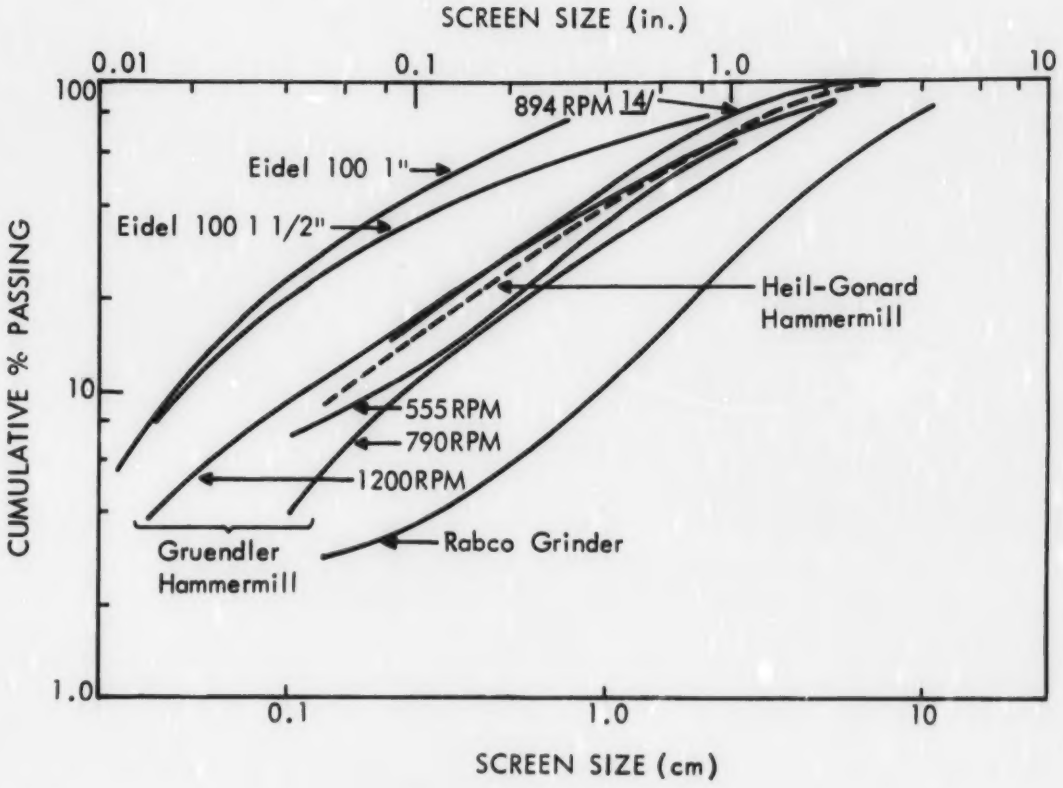
a/ Characteristic size was computed using method described in Ref. 12. Values in parentheses are in inches.

Table 6. PRODUCTION AND POWER USE AT ST. LOUIS SHREDDER DURING TEST PERIOD 9/30/74 - 11/18/74[14]

	Raw refuse processed[a]		Electrical power used[b]		Specific energy	
Week of	(Mg)	(tons)	(kw-hr)	(HP-hr)	kw-hr/Mg	HP-hr/ton
9-30	1,022	1,127	21,539	28,884	21.1	25.6
10-7	680	750	14,561	19,526	21.4	26.0
10-14	522	575	12,286	16,476	23.5	28.7
10-21	571	629	12,893	17,290	22.6	27.5
11-18	792	873	17,140	22,985	21.6	26.3

a/ Mg (tons) processed reported here are presented on a dry weight basis.

b/ Taken as 63% of total plant power. (The total rated horsepower of the shredder, all conveyor motors, magnetic drum, etc., amounts to 1,981.4 and the rated horsepower of the shredder alone is 1,250 or 63% of total. This assumes that all components are proportionately loaded.)



Note: Data for 555, 790, and 1,200 rpm were obtained from a laboratory unit whereas others were obtained from field units.16/

Figure 6. Size distribution of refuse from various shredders.12,14/

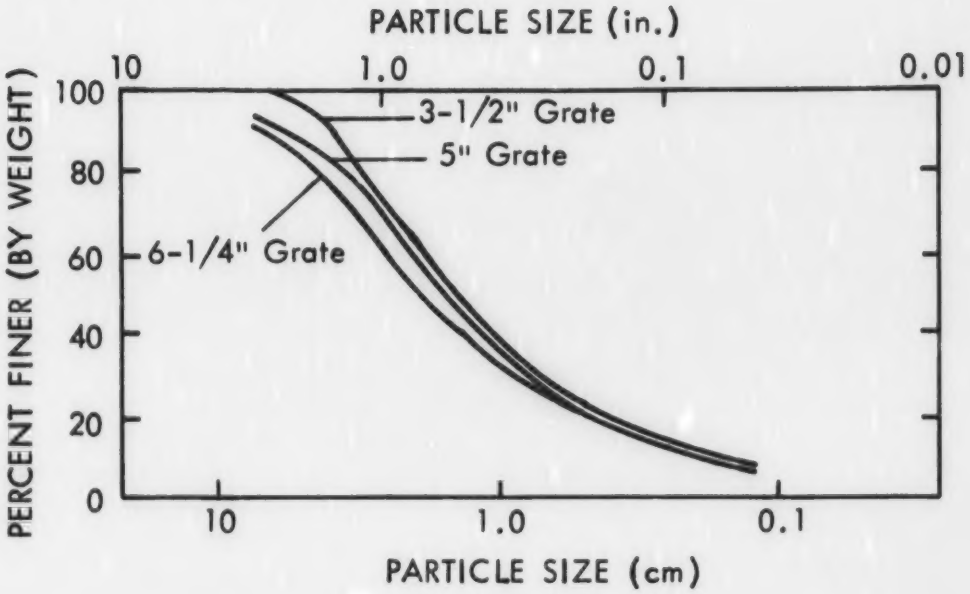


Figure 7. Effect of grate size on particle size distribution at Madison.[15]

Trezek[12] has shown, graphically, a relationship between grate spacing and a characteristic particle size, x_o, which has been discussed in the earlier section. This relationship has been reproduced in Figure 8. Product size distributions obtained from the St. Louis study[14] were used to obtain the range of characteristic particle size for the St. Louis shredder, as shown earlier in Table 5. This range was then plotted in Figure 8 to compare the grate spacing predicted by Trezek's curve with that actually observed in St. Louis. It can be seen from Figure 8 that the predicted grate spacing lies between 4.1 and 5.1 cm (1.6 and 2 in.), whereas the grate spacing in St. Louis was a 7.6-cm (3-in.) square. This disagreement could be due to differences in raw refuse composition. Also, the grate spacings reported by Trezek[12] were rectangular in shape with the indicated dimension being in a direction perpendicular to the axis of the mill shaft.[16] In summary, experience, as well as Refs. 12 and 15, indicates that smaller grate spacings yield a finer product size distribution.

Two contrasting observations are reported regarding the effect of moisture content on product size distribution.[9,12] The Madison study found the product size to be finer and more uniform with increase in moisture content.[9] This result is shown in Figure 9. The range of moisture content investigated was between 46 and 92%. Trezek[11] varied the moisture content between 37 and 63% and found increasing moisture content to result in a coarser size distribution as shown in Figure 10.

Rotor speed is generally believed to have a positive effect on product size distribution with higher speeds producing a finer product. Trezek[12] has investigated product size distributions with a 10 tons/hr Gruendler hammermill at speeds of 1,200, 790, and 555 rpm using grate bars with 6.4 cm (2-1/2 in.) openings. The grates were rectangular in shape with the 6.4 cm (2-1/2 in.) opening being perpendicular to the shaft; the opening parallel to the shaft was about 15.2 cm (6 in.).[16] For grinding speeds of 1,200, 790, and 555 rpm the corresponding average values of the characteristic particle size (x_o)* were 2.0, 2.7, and 2.2 cm (0.78, 1.08, and 0.88 in.).[12] Trezek claims that decreased speeds should usually produce a coarser product and increased speeds a finer product. However, at the two lower speeds (790 and 550 rpm) cited above, this is not the case. He has hypothesized that when a minimum speed is attained, the speed variable does not participate dominantly in the overall size reduction process.[12]

Hammer wear increases output particle size by progressively enlarging the clearance between the hammer tips and the housing. Figure 11 shows the effect of hammer wear on particle size distribution.[9]

---

* The characteristic particle size, x_o, has been defined earlier on page 21.

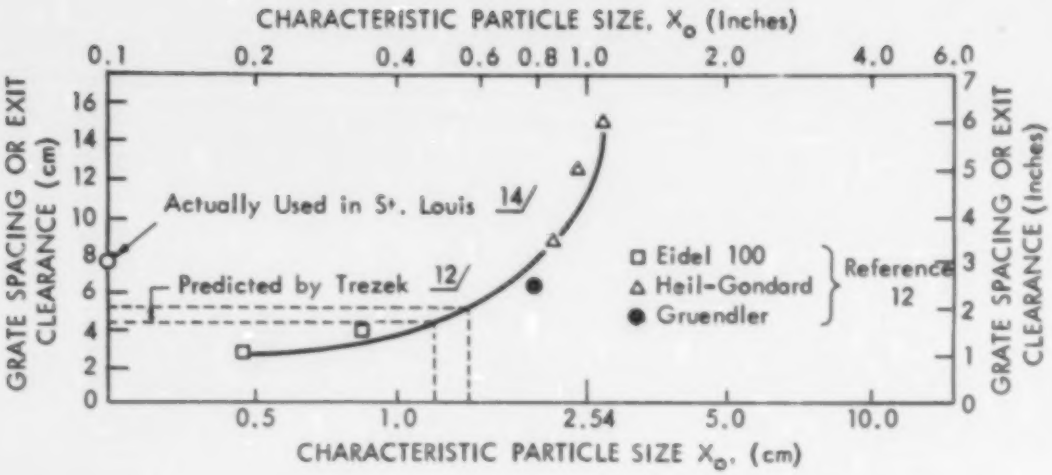


Figure 8. Characteristic particle size versus grate spacing.[12/]

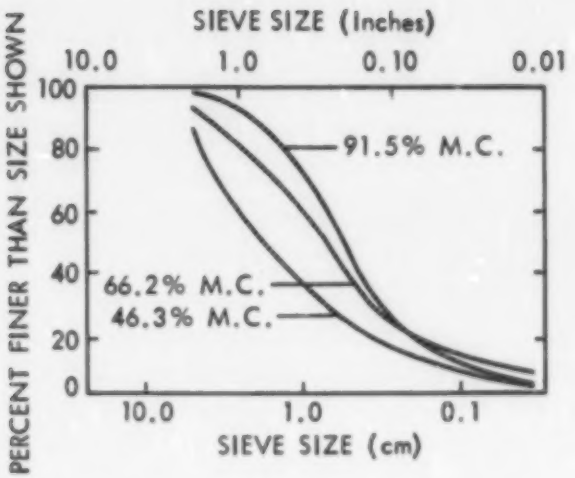


Figure 9. Effect of moisture content on particle size distribution.[9/]

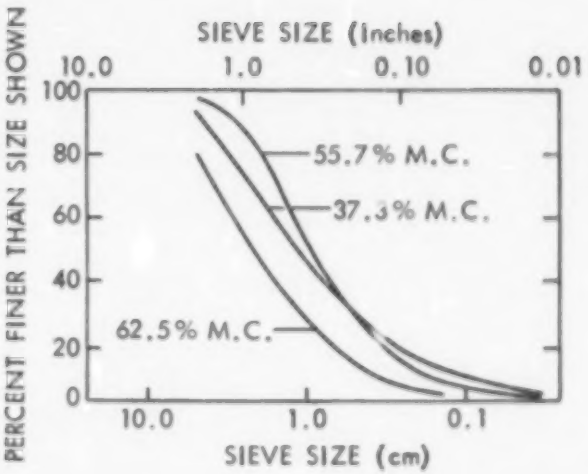


Figure 10. Effect of moisture content on particle size distribution.[11/]

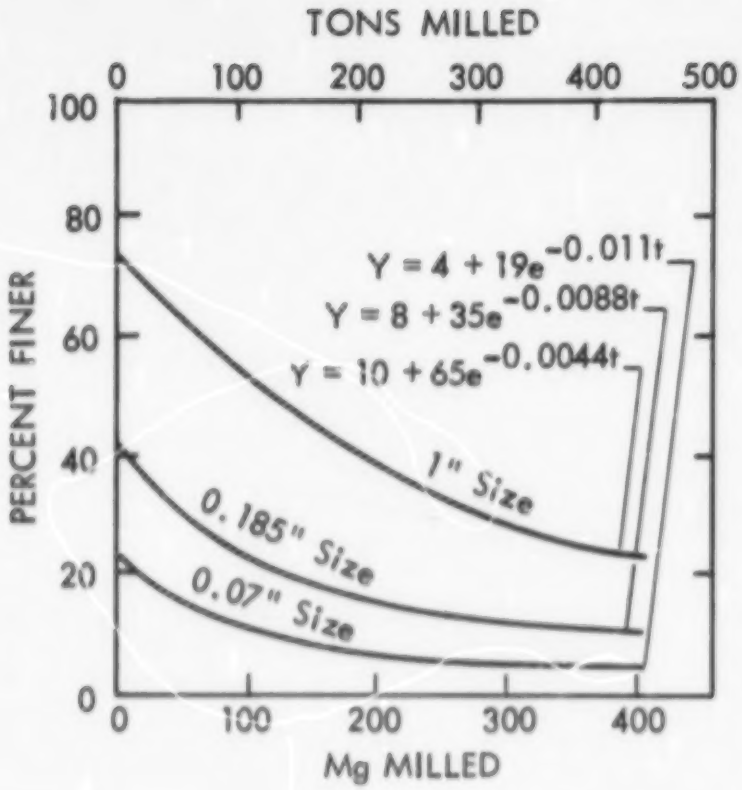


Figure 11. Changes in particle size distribution due to cumulative hammer wear.[9]

The data in Figure 11 clearly show the time dependency. The curves were described by the function $Y = b_o + b_1 \exp(-b_2 t)$ where Y is the weight percent of particles finer than the stated mesh size, t is the cumulative refuse milled (in Mg) since new hammers were installed, and the b's are empirical parameters.[9] It is also reported that hammer wear was a more significant variable than moisture content in affecting particle size distribution.[9]

Secondary and tertiary shredding obviously produce a finer product size distribution than primary shredding. This fact has been well documented in the literature.[8,11] The performance of the later stages will, however, vary with the amount of air classification or heavies separation that the feed undergoes after the primary shredder.

HAMMER WEAR

Hammer wear is closely related to shredder performance. Its effect on product size distribution has been discussed in the previous section.

Another aspect of "performance" is the need for replacements and maintenance of hammer tips and related components. In general, vertical hammer mills are believed to have lower wear rates than horizontal units and the wear also appears more evenly distributed in the vertical type.[17] Savage[18] discusses the effect of rotor speed and the effect of hard facing alloys on hammer wear. Table 7[18] shows the significance of both of these effects quantitatively and the data point out, that, at the lower speed nonhard faced hammers exhibit greater decrease in wear. If one had a choice of either reducing speed or hard facing the hammer, the former would be the more viable alternative. If the speed cannot be reduced, then hard facing of the hammers is imperative to prolong hammer life. The latter statement is also supported by the experience at Madison where the hammer life is increased almost five-fold on the Gondard mill as a result of hard facing.[10]

Table 7. AVERAGE WEAR FOR HAMMERS AND GRATE BARS UNDER DIFFERENT SPEEDS AND HAMMER FACING CONDITIONS[18]

	Average wear, kg/Mg (lb/ton)		Decrease in wear at lower speed
	1,200 rpm	790 rpm	
Full set of hard faced hammers	0.034 (0.068)	0.024 (0.047)	31%
Full set of nonhard faced hammers	0.054 (0.107)	0.031 (0.061)	43%
Grate bars	0.027 (0.053)	0.017 (0.034)	36%

SECTION IV

SHREDDER SELECTION

Generally shredders are selected based on motor horsepower using known throughputs and required product particle size. Therefore, we have reorganized data contained in Figure 5 to obtain a graphical relationship between power requirement (kw) and feed rate (Mg/hr) for different characteristic particle size, x_o . This relationship is shown in Figure 12. In deriving this figure, we used values from 0.51 to 5.1 cm (0.2 to 2 in.) for x_o and their corresponding specific energy consumption values (kw-hr/Mg) from Figure 5. We then assumed a linear relationship to exist between power requirement and feed rate. For example, for x_o = 2.0 cm (0.8 in.), the specific energy consumption = 16.3 kw-hr/Mg (19.8 HP-hr/ton) from Figure 5. This translates to 148 kw (198.3 HP) at a feed rate of 9.1 Mg/hr (10 tons/hr), for x_o = 2.0 cm (0.8 in.), and to 296 kw (396.6 HP) at a feed rate of 18.1 Mg/hr (20 tons/hr) for the same x_o . Since feed rate and power are assumed to be linearly related this will provide one line on Figure 12 for x_o = 2.0 cm (0.8 in.). Similarly, other lines were obtained for x_o values ranging from 0.51 to 5.1 cm (0.2 to 2 in.). It should be noted that the predictions are based on studies using typical municipal refuse. The actual power requirements would vary according to the size and nature of the material to be shredded. Reference 2 has reported suggested minimum horsepower for different waste categories and has tabulated power-output particle size--throughput relationships for some installations. Some other criteria involved in shredder selection are also presented.[2]

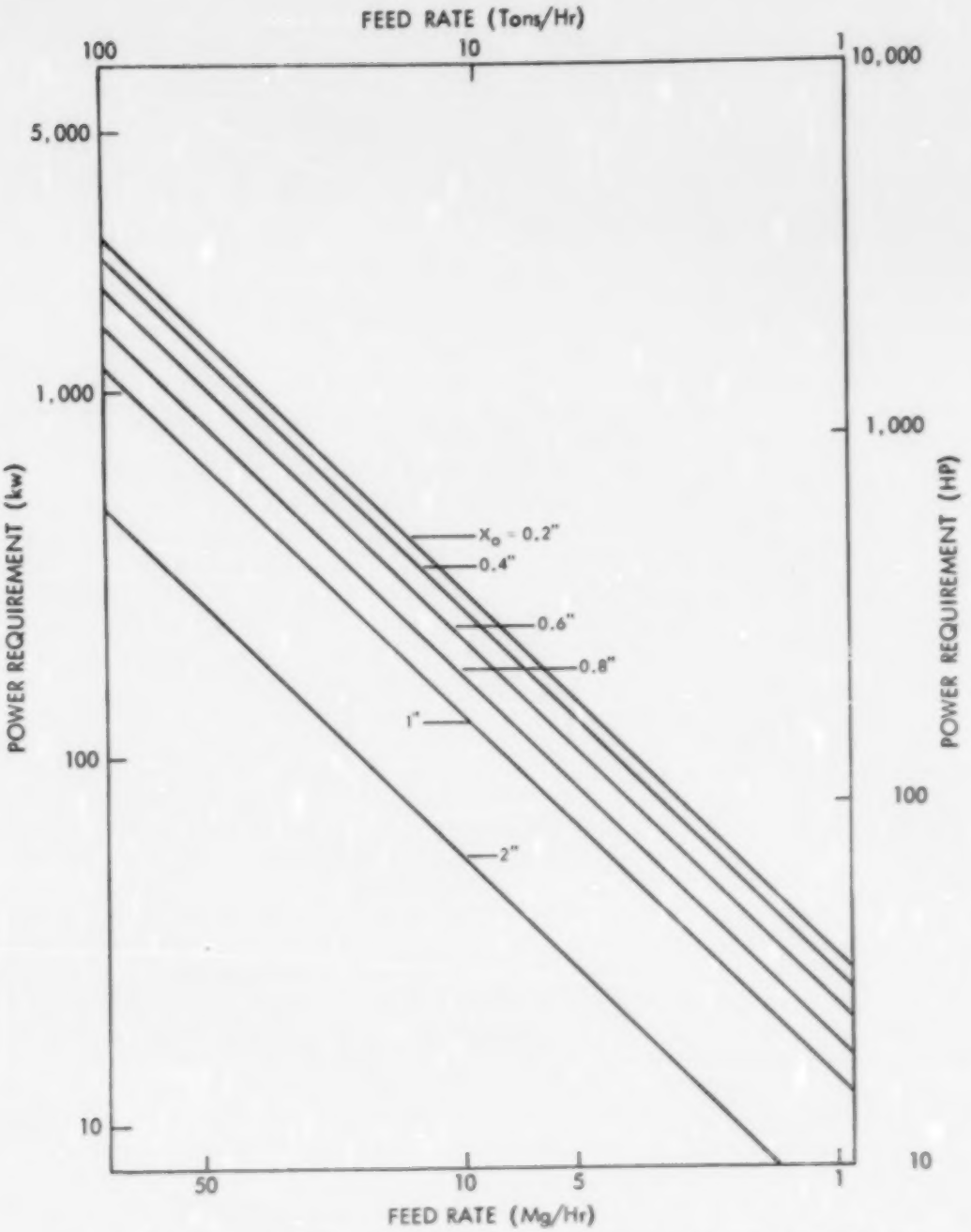


Figure 12. Power requirement as a function of feed rate and characteristic particle size desired (x_o refers to 63.2% cumulative passing in a Rosin-Rammler distribution as defined earlier).

SECTION V

SHREDDER COSTS

Available cost data are generally presented in different formats due to variations in bookkeeping practices. Therefore, ambiguities arise when direct comparisons or specific data are desired. Throughout this section we have attempted to present cost data in a comparable manner and have provided the basis for our interpretation of the available information.

The cost analysis has been broken down into capital, operating, and maintenance costs. Furthermore, the analysis includes only those costs which are directly associated with the shredder operation and does not take into account costs for building, ground, light, water, heat, etc.

CAPITAL COST

Information on capital costs for commercially available shredders is limited. The problem is enhanced by the fact that costs provided by different manufacturers are not readily comparable since some include accessories such as feed conveyors, hoppers, etc., and others do not. Also, the companies do not provide a breakdown for the cost of the accessories. Some shredder manufacturers also include the cost of an extra hammer set as part of the initial cost. In times of high inflation, the cost data also depend upon when the figures were released. Table 8 has attempted to eliminate some of these inconsistencies in reporting capital cost information for different types of shredders.

Table 9 provides capital cost values for shredders of equivalent size and identical accessories. These values were obtained from different manufacturers via their quotations for a recent shredder installation. From Table 9 the cost per megagram per hour is seen to vary from $3,500 to $6,200. Assuming an average capital cost of $4,410/Mg/hr ($4,000/ton/hr), estimated equipment life of 20 years with no salvage value, an interest rate of 6% and an operating time of 1,820 hr/year, the annualized capital cost was calculated using the following relationship.[10]

Table 8. INITIAL COST FOR SHREDDERS OF VARIOUS CAPACITIES

Manufacturer	Model	Capacity (Mg/hr)	Capacity (tons/hr)	Capital cost ($)	Cost per ton per hour ($)	Cost per Mg per hour ($)
Hammermills, Inc.[a]	4260	22	24	45,000[b]	1,875[b]	2,067[b]
				(88,000)[c]	(3,667)[c]	(4,043)[c]
	6060	29	32	80,000[b]	2,500[b]	2,756[b]
				(126,000)[c]	(3,938)[c]	(4,342)[c]
	6080	36	40	100,000[b]	2,500[b]	2,756[b]
				(151,000)[c]	(3,775)[c]	(4,162)[c]
	74104	73	80	(207,000)[c]	(2,588)[c]	(2,853)[c]
	96104	109	120	(300,000)[c]	(2,500)[c]	(4,342)[c]
American Pulverizer Company[d]	4200	9	10	12,300	1,230	1,356
	48-30	18	20	30,000	1,500	1,654
	60-30	27	30	25,600	853	940
	60-90	45	50	51,000	1,020	1,125
	72-72	91	100	153,000	1,530	1,687
	72-84	91	100	167,000	1,670	1,841
	96-90	136	150	259,000	1,727	1,904
The Heil Company[e]	42-D	14	15	76,000	5,100	5,623
	42-F	18	20	86,000	4,300	4,741
	92-(500 HP)	45	50	255,000	5,100	5,623
	92-(750 HP)	54	60	260,000	4,300	4,741
	92-(1,000 HP)	68	75	267,000	3,560	3,925
The Carborundum Company[f]	100	1-4	1-4	18,000	7,200[g]	7,938[g]
	400	14-32	15-35	38,000	1,520[g]	1,676[g]
	1000	27-50	30-55	100,000	2,352[g]	2,593[g]

a/ Source: Hammermills, Inc., Bulletin 1972. Prices quoted are for basic shredders only; feed conveyors, hoppers, chutes, power, etc., are not included.

b/ Standard model.

c/ Compression fedder model.

d/ Source: American Pulverizer Company, Bulletin R71 and private communication in November 1975 and June 1975 with Mr. Lin Baker.

e/ Private communication with Mr. Erv Domanski of Heil Company in November 1975 and June 1976. The company usually furnishes shredder and the auxiliary systems and costs reported here are approximated for shredder alone by using 40% of total cost.

f/ Source: The Carborundum Company provided total cost of shredder and accessories such as discharge chute, infeed hood, motor, and controls. Cost for shredder alone had to be computed assuming 40% of total cost to be applicable to shredder.

g/ Computed with mean capacity.

Table 9. INITIAL COST FOR SHREDDERS OF EQUIVALENT SIZE

Manufacturer	Capacity[a] (Mg/hr)	Capacity[a] (tons/hr)	Capital cost[b] ($)	Cost per unit capacity ($/Mg/hr)	Cost per unit capacity ($/ton/hr)
A	45	50	160,000	3,500	3,200
B	45	50	190,000	4,200	3,800
C	45	50	210,000	4,600	4,200
D	45	50	280,000	6,200	5,600
E	45	50	230,000	5,100	4,600
F	45	50	280,000	6,200	5,600

a/ Capacities for MSW.

b/ Capital cost includes infeed conveyors, motors, and other accessories.

$$AC = (P-L)\,(CRF) - Li$$

Where AC = annualized capital cost

P = initial cost

L = salvage value

CRF = capital recovery factor

i = interest rate.

The computed values are shown in Table 10. It can be seen from Table 10 that the annualized cost per megagram is constant and independent of the rated capacity. The estimated unit cost (cost/Mg) is compared with those reported for the Gainesville, Madison and St. Louis plants[10,19] in Table 11. It is obvious that factors such as assumed equipment life, interest rate, and machine operating hours affect the unit cost. Of these, the most sensitive appears to be the operating time. For example, an increase of operating time from 5 to 8 hr/day in Madison would have significantly reduced unit costs of the Gondard and Tollemache mills from $1.21 to $0.84/Mg ($1.10 to $0.76/ton) and from $0.49 to $0.31/Mg ($0.44 to $0.28/ton), respectively. Thus, all of these factors must be considered when comparisons are made.

The addition of a secondary shredder can be guided by factors such as ultimate product size desired, amount and extent of resource material to be recovered, capital and maintenance costs, etc. However, private communication with industry personnel indicates that the major advantage may be one of reducing maintenance costs. At this point, we can only say that capital costs will increase with multi-stage shredding. The data base on hand is inadequate to conclusively determine the benefits of multi-stage shredding. Such information may become available when the Ames project gets underway.

Information on maintenance and operating cost is scarce and even the available information is not amenable for direct comparison between different systems. Therefore, we have used estimated costs provided by manufacturers and compared them with actually observed values whenever possible. This discussion is contained in the following sections.

MAINTENANCE COSTS

Maintenance costs reported by manufacturers are generally variable. Table 12 shows maintenance costs associated with various parts of two particular shredders.

Table 10. ESTIMATED ANNUALIZED CAPITAL COST

Capacity (Mg/hr)	Capacity (tons/hr)	Refuse processed per year[a] (Mg)	Refuse processed per year[a] (tons)	Annualized capital cost[b] based on capacity ($)	Annualized capital cost based on refuse processed annually ($/Mg)	Annualized capital cost based on refuse processed annually ($/ton)
9.07	10	16,500	18,200	3,487	0.21	0.19
45.35	50	82,500	91,000	17,436	0.21	0.19
90.7	100	165,000	182,000	34,872	0.21	0.19

a/ Assuming single-shift operation with machine running 5 days/week at 7 hr/day and 1 hr of general maintenance or cleanup.

b/ Assuming a capital cost of $4,410/Mg/hr (4,000/ton/hr), zero salvage value, equipment life of 20 years, and 6% interest rate.

Table 11. COMPARISON OF UNIT COSTS FOR MADISON AND GAINESVILLE PLANTS

	Estimates based on Table 10	Madison, Wisconsin, plant		Gainesville, Florida, plant (Williams Hammermill)		St. Louis refuse processing plant (Gruendler 60 x 84)
		Gondard Mill	Tollemache Mill	Primary unit	Secondary unit	
Shredder capacity						
Mg/hr	9.1, 45 and 91	7.3	14	27	18	45
tons/hr	10, 50 and 100	8	15	30	20	50
Unit cost						
$/Mg	0.21	1.21[a,b]	0.49[a,c]	0.22[d]	0.18[d]	0.32[e]
$/ton	0.19	1.10[a,b]	0.44[a,c]	0.20[d]	0.16[d]	0.29[e]

a/ Costs include conveyors.

b/ Computation based on $4,000 salvage value, equipment life of 15 years, 5.8% interest, and 5.5 hr/day (for June 1968-May 1969).

c/ Computation based on $4,000 salvage value, equipment life of 15 years, 5.9% interest, and 5.3 hr/day (for July 6-October 9, 1970).

d/ Costs include motor, starter, extra hammer set, transportation, structural support, installation, and consultants. Amortization based on effective interest rate of 6% over 10-year period. Machine operating time was 8 to 10 hr/day (for July-October 1969).

e/ Costs include motor. Amortization based on interest rate of 6% and 20 years capital recovery. Values are for October 1974-September 1975. Monthly average ranges from $0.15 to $2.17/Mg ($0.14 to $1.97/ton). Source: Midwest Research Institute, Final Draft Report to EPA on Contract No. 68-02-1324 and Contract No. 68-02-1871, March 19, 1976).

Table 12. MAINTENANCE COST FOR VARIOUS COMPONENTS OF TWO SHREDDER UNITS

Manufacturer	Part	Estimated maintenance cost, $/Mg ($/ton) Material	Labor	Total[a]	Other information
Hammermills, Inc.[b]	Hammers	0.14 (0.13)	0.03 (0.03)[c]		Model 6080 shredder with force feed, reversible hammers, requires no tipping, nominal product size 7.6 cm (3 in.)
	Cutter bar	0.08 (0.07)	0.07 (0.06)[c]	0.32 (0.29)	
Gruendler Crusher[d] and Pulverizer Company	Hammers	0.103 (0.093)	0.120 (0.109)[e]		Model 60X84 shredder, reversible hammer, product size 10-15 cm (4-6 in.)
	Side liner	0.0326 (0.0296)	0.0018 (0.0016)[e]		
	Grate	0.0841 (0.0763)	0.0009 (0.0008)[e]		
	Pin	0.012 (0.011)	-	0.39 (0.35)	
	Top anvil	0.017 (0.015)	0.0008 (0.0007)[e]		
	Breaker plates	0.017 (0.015)	0.0008 (0.0007)[e]		

[a] Total cost does not include electric power used for maintenance.
[b] Company estimates based on figures from the City of Harrisburg, Pennsylvania.
[c] Labor cost computed at $15/hr.
[d] Manufacturer estimates for City of Omaha, Nebraska.
[e] Labor cost computed at $10/hr.

Hammermills, Inc., released only maintenance cost for hammers and cutter bar. A more detailed breakdown on the maintenance expenses was given by Gruendler Crusher and Pulverizer Company. The total cost of maintenance reported in Table 12 does not include costs for minor maintenance on bearings, seals, motors, etc., nor replacement of shaft and rotor. However, data shown in Table 13 include maintenance costs for motors, feed conveyors, and other accessories and are thus higher than those in Table 12. Values contained in Table 13 were estimated by the manufacturers. Because of the lack of field data on these specific shredders we have not been able to compare manufacturers' maintenance data with those actually experienced.

Maintenance costs observed at Madison and Gainesville shredders are shown in Table 14.[10,19] Even though manufacturer supplied maintenance data are not available for comparison, we have included them to provide an indication of costs actually experienced. In each case, the cost can be reduced by proper maintenance such as frequent examination of hammers and associated components, and hard facing and tipping. In Madison, such procedures resulted in a savings of 25¢/Mg (23¢/ton) processed.[10]

When a secondary unit is used, the maintenance cost for both units together is claimed to be lower than when one unit alone is operating to achieve the required product size. However, this claim has not been documented.

OPERATING COST

Operating costs have been computed for three different capacities, 9.1, 45, and 91 Mg/hr (10, 50, and 100 tons/hr) based on the following assumptions.

1. Single shift operation for 5 days/week at 7 hr/day for production, and 1 hr/day for general maintenance and cleanup.

2. One man working full time and another working halftime are used for operating the shredder and for general maintenance at $7.00/man-hour.

3. Typical value of 20.6 kw-hr/Mg (25 HP-hr/ton) for MSW is used for computing energy cost.

4. Power cost is $0.02/kw-hr (even though this is generally variable, we believe that this rate would be a good overall average rate).

The operating costs for plant capacities of 9.1, 45, and 91 Mg/hr (10, 50, and 100 tons/hr) are shown in Table 15.

Table 13. MAINTENANCE COST FOR (45 Mg/hr) SHREDDER UNITS AS PROVIDED BY MANUFACTURERS[a]

Manufacturer	Estimated maintenance cost, $/Mg ($/ton) Material	Labor[b]	Total[c]	Other information
Pennsylvania Crusher Corporation	0.25 (0.23)	0.12 (0.11)	0.37 (0.34)	Model BW-6080, horizontal shaft design, 746 kw (1,000 HP)
Carborundum Company	0.35 (0.32)	0.09 (0.08)	0.44 (0.40)	Model 1000, vertical shaft design, 373 kw (500 HP)
American Pulverizer Company	0.20 (0.18)	0.42 (0.38)	0.62 (0.56)	Model 60X90, horiziontal shaft design, reversible rotor, 746 kw (1,000 HP)
Heil Company	0.61 (0.55)	0.11 (0.10)	0.72 (0.65)	Model 92-A, vertical shaft design, reversible hammer, 373 kw (500 HP)
Jeffrey Manufacturing Company	0.62 (0.56)	0.18 (0.16)	0.79 (0.72)	Model 990, horizontal shaft design, 746 kw (1,000 HP)
Gruendler Crusher and Pulverizer Company	0.47 (0.43)	0.35 (0.32)	0.83 (0.75)	Model 60X84, horizontal shaft design, reversible hammer, 746 kw (1,000 HP)

a/ For typical product size of 10-15 cm (4-6 in.).
b/ Labor cost computed at $15/hr.
c/ Total cost includes maintenance for feed conveyors, motors, and other accessories.

Table 14. MAINTENANCE COSTS OBSERVED AT MADISON[10]/ AND GAINESVILLE[19]/

Grinder	Part	Maintenance cost, $/Mg ($/ton) Material	Labor	Power	Total
Gondard Mill (Madison, 1969)a/	Hammer wear	0.17 (0.15)	0.46 (0.42)b/	-	1.40 (1.27)
	Mill maintenance	0.20 (0.18)c/	0.57 (0.52)b/	-	
Tollemache Mill (Madison, 1969)d/	Hammer and shaft	0.151 (0.137)	0.36 (0.33)b/	-	1.077 (0.977)
	Welding rod	0.036 (0.033)	-	-	
	Mill maintenance	0.074 (0.067)e/	0.45 (0.41)b/	-	
Williams Hammermill (Gainesville, 1969 - primary unit)	Hammer build-up	0.093 (0.084)	0.157 (0.142)f/	0.300 (0.027)	0.834 (0.756)
	Maintenance and repairs	0.359 (0.326)	0.195 (0.177)f/	-	
Williams Hammermill (Gainesville, 1969 - secondary unit)	Hammer build-up	0.040 (0.036)	0.265 (0.240)f/	0.031 (0.028)	1.012 (0.918)
	Maintenance and repairs	0.466 (0.423)	0.100 (0.091)f/	-	

a/ Cost data are for operation with grate size of 12.7 cm (5 in.), June 1968-May 1969.
b/ During a different test period in Madison, labor costs for hammer and repair maintenance were 12 and 15% of total labor cost. These values are used in computing the labor cost here.
c/ Material cost includes those for mill maintenance and general supplies.
d/ Cost data are for test period July 6-October 9, 1970.
e/ Plant supplies and replacement parts.
f/ Labor cost includes fringe benefits.

Table 15. ESTIMATED OPERATING COST FOR PRIMARY SHREDDER UNITS

Capacity		Refuse processed per year[a]		Power[b]			Labor[c]			Total operating cost		
(Mg/hr)	(tons/hr)	(Mg)	(tons)	Annual ($)	Cost Mg ($)	Cost ton ($)	Annual ($)	Cost Mg ($)	Cost ton ($)	Annual ($)	Cost Mg ($)	Cost ton ($)
9.1	10	16,500	18,200	6,825	0.42	0.38	21,840	1.32	1.20	22,665	1.74	1.58
45	50	82,500	91,000	34,125	0.42	0.38	21,840	0.26	0.24	55,965	0.68	0.62
91	100	165,000	182,000	68,250	0.42	0.38	21,840	0.13	0.12	90,090	0.55	0.50

a/ Single-shift operation with machine running 5 days/week at 7 hr/day for production and 1 hr of general maintenance or clean-up.

b/ At 20.6 kw-hr/Mg (25 HP-hr/ton) for MSW and $0.02/kw-hr.

c/ One and one-half men at $7/hr.

Based on present assumptions, power cost per megagram remains the same for any capacity while labor cost per megagram decreases with capacity. Figure 13 shows the operating costs for various capacities obtained from Table 15. The operating cost decreases with increase in capacity and is asymptotic at about 91 Mg/hr (100 tons/hr). The figure also shows the operating cost observed at the Madison and Gainesville shredding facilities.[10,19] Differences in operating cost can be caused by variations in operating capacity, power consumption (due to variations in shredder design), labor wage rates, number of operators employed, etc. Therefore, the differences observed are not highly significant.

The operating cost for a secondary unit is expected to be slightly lower than that of the primary unit due to reduced power consumption as a result of smaller and more uniform input material. This expectation is observed in Figure 13 for the Gainesville secondary unit. Also, air classification systems following the primary unit would help reduce the amount of heavier input material and hence conserve energy.

COMBINED COST

The combined cost of shredding MSW has been estimated using the capital, maintenance, and operating costs (discussed above). This cost is tabulated in Table 16 and shown in Figure 14. On a per-megagram basis, the maintenance and operating costs are the dominant factors. Figure 14 also compares the estimated combined cost with actual costs observed at the Gainesville, Madison, and St. Louis plants. The Gainesville facility is a two-stage operation and the combined cost for each stage was obtained from Ref. 19. The St. Louis cost data are reported for the entire processing plant including the shredder, air density separator, magnetic separator, nuggetizer, etc., and we have not been able to identify shredder costs separately. Therefore, the St. Louis costs are higher than those estimated. The Madison costs are also higher than the estimated costs. This is probably because it was one of the earliest facilities to go into operation.

The estimated cost curve in Figure 14 shows a minimum at about 68 Mg/hr (75 tons/hr) rated capacity. Even though this may not be the exact optimum capacity for a new facility, it certainly indicates that one should seek an optimum value in designing or selecting a shredder.

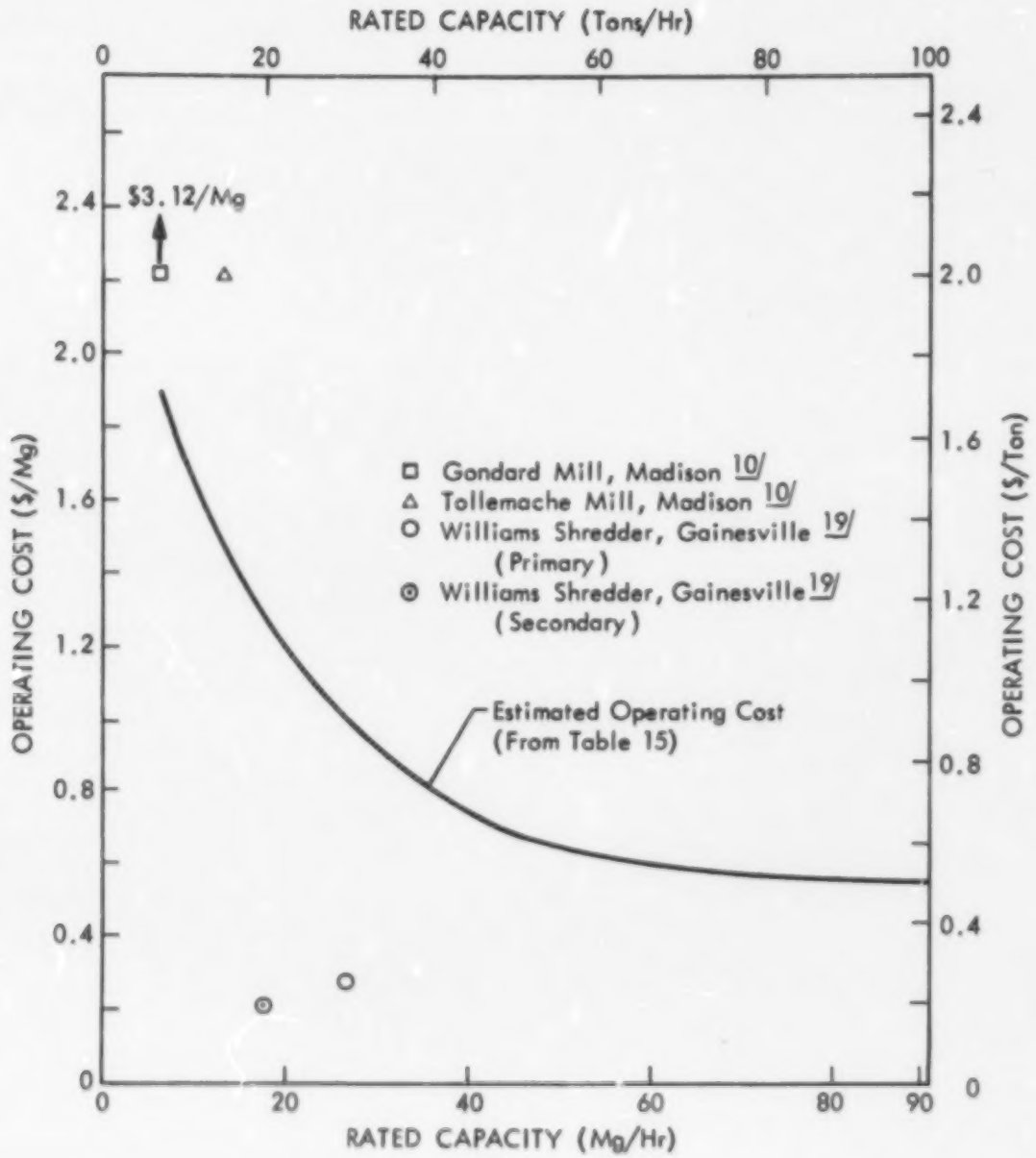


Figure 13. Estimated operating cost for various shredder capacities.

Table 16. COMBINED COST OF SHREDDING MSW

Capacity		Capital cost[a]		Maintenance cost[b]		Operating cost[c]		Combined cost	
(Mg/hr)	(tons/hr)	($/Mg)	($/ton)	($/Mg)	($/ton)	($/Mg)	($/ton)	($/Mg)	($/ton)
9.1	10	0.21	0.19	0.33	0.30	1.74	1.58	2.28	2.07
45	50	0.21	0.19	0.55	0.50	0.68	0.62	1.44	1.31
91	100	0.21	0.19	0.77	0.70	0.55	0.50	1.53	1.39

a/ From Table 10.
b/ Estimate based on private communication with manufacturers.
c/ From Table 15.

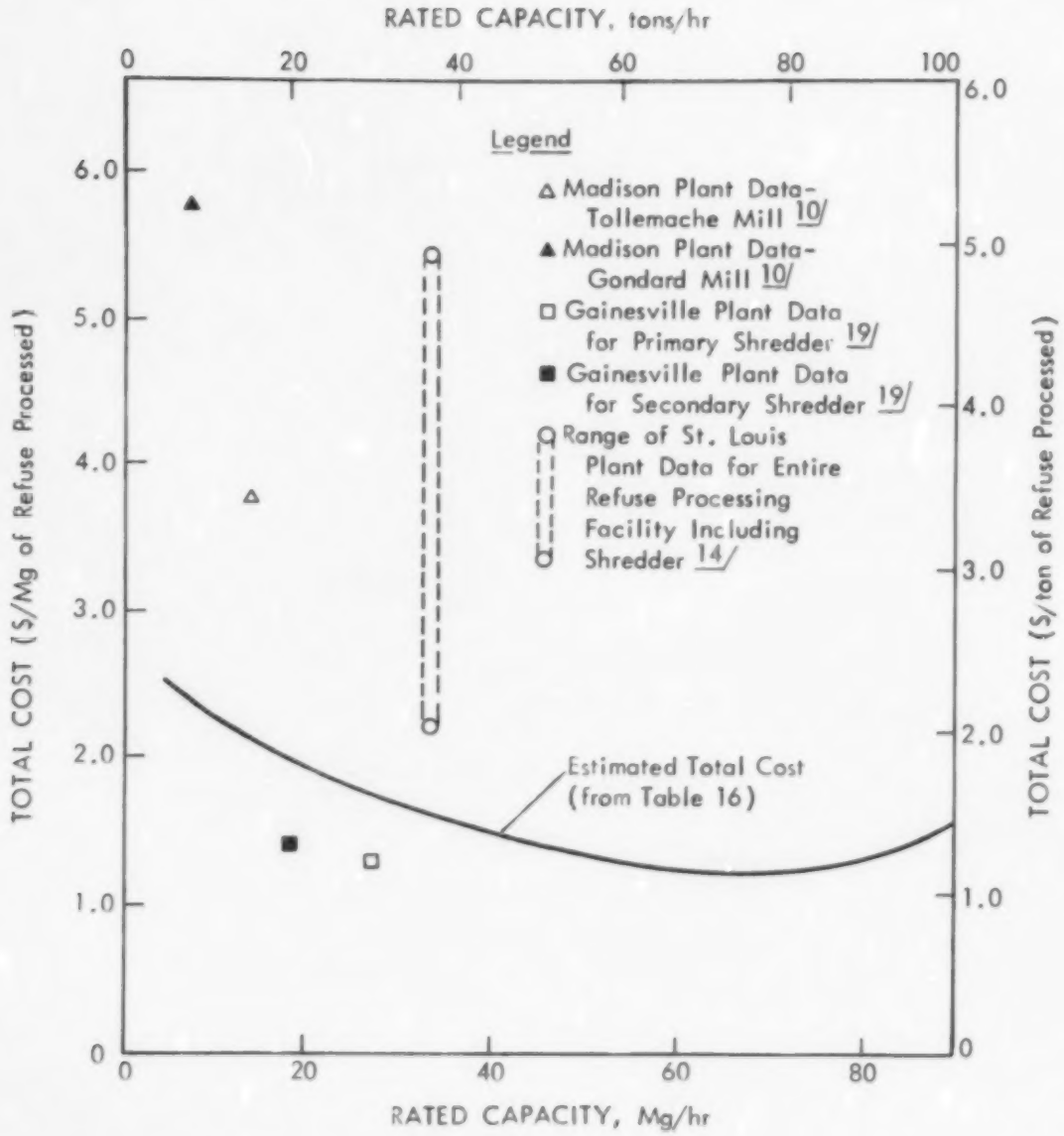


Figure 14. Total cost versus rated capacity.

SECTION VI

EVALUATION OF MATERIAL/ENERGY RECOVERY SYSTEMS

We have evaluated material/energy recovery systems such as pyrolysis and combined firing (coal-refuse) to determine the cost and performance benefits resulting from shredding refuse to finer levels. The specific processes that were studied are shown in Table 17. In addition, we have contacted operators of these systems to obtain information on process constraints which dictate the need for shredding, the maximum particle size the system can tolerate, and performance improvements that result from finer particles. Cost benefits which might accrue due to enhanced material recovery or performance were also sought. The available information is summarized below. It should be noted that the emphasis is on the shredding aspects of these systems.

Table 17. PYROLYSIS AND COMBINED FIRING SYSTEMS INVESTIGATED TO DETERMINE THE BENEFITS OF FINE SHREDDING

Pyrolysis
• Monsanto Landgard system
• Union Carbide Purox process
• Occidental Petroleum Garrett process
• Battelle Northwest pyrolysis system
• West Virginia University pyrolysis process
Combined firing
• Horner-Shifrin supplementary fuel process (St. Louis, Ames)

PYROLYSIS SYSTEMS

In the Monsanto Landgard system, which is operational at Baltimore, mixed municipal solid waste is shredded to approximately 10.2 cm (4 in.)

in one of two 45 Mg/hr (50 tons/hr) shredders. It is then fed into a refractory lined rotary kiln which acts as the pyrolyzer. No additional information is available on the shredding aspects to permit an evaluation of cost/performance benefits of this system.

The Linde Division of Union Carbide Corporation has developed a high temperature pyrolysis system, called the Purox system, which utilizes nearly pure oxygen for the combustion of pyrolysis char. The main advantage of using pure oxygen is that the pyrolysis gas is free of nitrogen. The Purox system originally did not utilize shredded refuse as feed into the pyrolysis reactor but recently the refuse is being shredded to a typical size of 15.2 cm (6 in.). It is claimed[20] that the maximum particle size the system can tolerate is 22.9 cm (9 in.) and that the system is guaranteed only for shredded refuse. No other data are currently available to us.

Occidental Petroleum's Garrett pyrolysis process is a "flash" pyrolysis process which requires most nonorganic material to be removed from the refuse feed. The process also requires the organic material to be reduced to small, dry particles. Therefore, the feed (MSW) is first shredded to a particle size of 7.6 to 10.2 cm (3 to 4 in.) in a primary shredder.[21] It is then air classified to separate the light, organic fraction from the heavy, inorganic fraction. The lights are then dried to a moisture content of 3%. A screen is used to remove additional inorganics and the remaining material is again shredded to a particle size of -20 to -30 mesh.[21]

Table 18 shows a typical size distribution of prepared refuse for the Garrett process.[3] It is claimed that the system will not work without secondary shredding due to the very short residence time in the reactor.[21] Cost data on the system are not available to us.

Battelle Northwest has conducted experiments in a vertical shaft pyrolysis reactor with shredded, unsegregated refuse at a feed rate of about 81.6 kg/hr (180 lb/hr). The size of refuse is about 30.5 cm (12 in.) across and it is believed that fine shredding of the refuse will plug up the reactor bed and hamper the process.[22]

The West Virginia University pyrolysis process makes use of two fluidized beds; one for pyrolysis and another for combustion. The refuse entering the pyrolysis (fluidized bed) reactor is shredded, classified, and dried. Initial experiments demonstrated the need for preprocessing raw refuse. The Stanford Research Institute study[23] recommended a maximum particle size of 2.5 cm (1 in.) but systematic investigations relating effect of particle size or performance/cost benefits have not yet been undertaken.[24]

Table 18. SIZE DISTRIBUTION OF GARRETT SECONDARY SHREDDED SOLID WASTE[3/] (ORGANIC PORTION ONLY)

Size		
Tyler mesh (in.)	Microns	Wt. % retained
1/4	6,350	6.0
16	991	21.0
20	833	3.9
32	495	19.1
48	295	11.7
80	175	9.1
100	147	4.8
150	104	4.6
200	74	4.9
-200	-74	14.9

Note: Solid waste ground to this size is of a matted, fibrous nature. Screen size is not an accurate measure of particle length or width particularly above 20 mesh where considerable "balling" is apparent.

COMBINED FIRING SYSTEMS

The Horner-Shifrin process is used in the St. Louis project.[14] This project is demonstrating the feasibility of using processed municipal refuse as a supplementary fuel with coal in a power plant boiler. The raw municipal solid waste goes through a hammermill where it is reduced to less than 6.35 cm (2.5 in.) in size. It is then passed through an air classifier which separates it into a light fraction and a heavy fraction. From the heavy fraction, ferrous metals are recovered using a magnetic drum and the nonmagnetic metals and glass go to a landfill. The light fraction is used as the supplemental fuel for the power plant boiler. Table 19 shows the typical size distribution for the shredded, air classified refuse. Cost data are reported for the entire processing plant and we have not been able to identify shredder costs independently. The same difficulty was also encountered in evaluating the shredder performance independent of other systems at the processing facility. Union Electric engineers claim that fine shredding of refuse does result in better heat recovery. They interpret a higher heat recovery with refuse ground to less than 3.18 cm (1.25 in.) when compared to refuse less than 7.6 cm (3 in.) in size based upon megawatts generated per megagram of refuse.[25] The St. Louis study, however, reports that the combustion efficiency did not improve with fine ground refuse when based on the two data points for fine-ground refuse.[26]

Table 19. TYPICAL SIZE DISTRIBUTION OF SHREDDED, AIR CLASSIFIED REFUSE IN ST. LOUIS[14]

Size	
Percent larger than 6.4 cm (2.5 in.)	2.5
Percent less than 6.4 cm (2.5 in.)	97.5
Percent less than 3.8 cm (1.5 in.)	94.0
Percent less than 1.9 cm (0.75 in.)	73.5
Percent less than 0.95 cm (0.375 in.)	49.0
Percent less than 0.47 cm (0.187 in.)	31.9
Percent less than 0.24 cm (0.094 in.)	21.2

The Ames project which is expected to commence shortly will be addressing many of the aspects that could not be covered in the St. Louis study. For instance, it will be the first operating refuse shredding/firing facility to use magnetic separation between two 45 Mg/hr (50 tons/hr) shredders and an air classifier following the second shredder. Such a setup

should provide field data on the benefits of two-stage shredding, variations in energy consumption between the two stages and variations in maintenance and operating costs. Much of these data are presently unavailable.

SUMMARY

Our review of the available information and our conversations with operators of material/energy recovery systems indicate that process constraints primarily dictate the need for shredding refuse. It is logical to assume that fine shredding will enhance energy recovery by improving the combustion/thermal reaction efficiency. Also, material recovery should improve with fine shredding particularly in air separators. However, field test data documenting these aspects are currently not available. The inclusion of fine shredding capability in the overall system, to reduce the product size distribution, will increase capital costs, but in the long run, the system's enhanced performance both in terms of energy recovery and in terms of material recovery may help offset this additional cost. In fluidized bed systems, however, the need for fine shredding has to be critically evaluated in conjunction with bed characteristics. At present the available data are insufficient to make any definite conclusions.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

Most of the reported field data on shredders including performance and costs are related to the Madison, Gainesville, and St. Louis studies. Our discussion has been based on these studies as well as those of Trezek at the University of California, Berkeley.

Several factors affect shredder performance and these include feed moisture content, shaft speed, grate spacing, feed composition, and particle size distribution. Of these, the effects of feed composition and feed particle size distribution on the specific energy consumption and product size distribution are not well characterized. Also, all of these factors should be studied on field units and under field conditions.

Cost data are available for specific shredder installations, but due to different bookkeeping systems, we have found it difficult to compare costs directly. Our estimates indicate that the capital cost is about \$4,410/Mg/hr (\$4,000/ton/hr), and the annualized unit cost (excluding operating and maintenance costs) is \$0.21/Mg (\$0.19/ton). Maintenance and operating costs were estimated to be about \$0.33 and \$1.74/Mg (\$0.3 and \$1.58/ton), respectively, for a throughput of 9.1 Mg/hr (10 tons/hr); for a throughput of 91 Mg/hr (100 tons/hr), they were about \$0.77/Mg (\$0.7/ton) for maintenance costs and \$0.55/Mg (\$0.5/ton) for operating costs. All of these costs, however, should be used with caution.

Evaluation of material/energy recovery processes such as pyrolysis and combined firing systems indicates the apparent lack of quantitative information on the cost/performance benefits of fine shredding in such systems. We feel that process constraints dictate the need for shredding in such processes.

Based on the above observations, it is recommended that tests be conducted in the field to systematically characterize the effect of variables affecting shredder performance. These tests are critical to optimize shredder performance and to establish design criteria for obtaining required product size distribution and throughput. During these tests, the performance of the overall material/energy recovery process should also be

systematically studied to establish the optimum particle size required and to evaluate the benefits of fine shredding in such systems. In conjunction with these tests, it is imperative that cost data also be collected in a systematic, standardized manner throughout the process to (a) determine operating and maintenance costs, and (b) evaluate cost benefits, if any, that may arise from shredding refuse to finer levels in material/energy recovery processes.

Projects utilizing municipal solid waste either as supplemental fuel or as principal fuel are underway at Ames and Baltimore, respectively. As discussed earlier, both of these processes require the refuse to be shredded prior to combustion/pyrolysis. Also, the University of California at Berkeley is currently involved in a fine shredding study. It is therefore recommended that these studies incorporate performance/cost evaluation of the overall system, including shredding operations, along the lines outlined above. Future projects should acquire such data, as part of the overall effort, in order to provide an adequate data base for any type of definitive analysis.

REFERENCES

1. "Inventory of Municipal Solid Waste Size Reduction Equipment," prepared by Midwest Research Institute for EPA under Contract No. 68-03-0137, June 1973.

2. "Solid Waste Shredding and Shredder Selection," EPA Publication No. EPA/530/SW-140, March 1975.

3. "Energy Recovery from Solid Waste," Vol. II, NASA-ASEE 1974 Systems Design Institute NASA Grant NGT-44-005-114, September 1974.

4. Trezek, G. J., "Size Reduction Equipment," Compost Science, pp. 22-25, September/October 1973.

5. Private communication with Mr. H. D. Funk of Henningson, Durham, and Richardson, Omaha, Nebraska.

6. "Combined Firing Applications Study," prepared by Midwest Research Institute under EPA Contract No. 68-02-1324, Task 20, December 1974.

7. Waste Age, pp. 10-15, July 1975.

8. Ruf, J. A., "Particle Size Spectrum and Compressibility of Raw and Shredded Municipal Solid Waste," Ph.D. Thesis, University of Florida, 1974.

9. Gawalpanchi, R. R., P. M. Berthouex, and R. K. Ham, "Particle Size Distribution of Milled Refuse," Waste Age, pp. 34-74, September/October 1973.

10. Reinhardt, J. J., and R. K. Ham, Final Report on a Demonstration Project at Madison, Wisconsin, to Investigate Milling of Solid Wastes, Vol. I, 1966-1972, EPA Office of SWMP, March 1973.

11. Trezek, G. J., D. M. Obeng, and G. Savage, "Size Reduction in Solid Waste Processing," 2nd Year Progress Report 1972-1973, College of Engineering, University of California, Berkeley.

12. Trezek, G. J., and G. Savage, "Results of a Comprehensive Refuse Comminution Study," Waste Age, pp. 49-55, July 1975.

13. Obeng, D. M., and G. J. Trezek, "Simulation of the Communition of a Heterogeneous Mixture of Brittle and Nonbrittle Material in a Swing Hammermill," Ind. Eng. Chem. Process Des. Dev., 14(2):113, 1975.

14. Shannon, L. J., D. E. Fiscus, and P. G. Gorman, "St. Louis Refuse Processing Plant: Equipment, Facility and Environmental Evaluations," EPA Publication No. EPA-650/2-75-044, May 1975.

15. "Solid Waste Reduction/Salvage Plant," 3rd Progress Report, City of Madison Pilot Plant, June 14, 1967 through December 28, 1968, prepared by project personnel at Madison, Wisconsin, for the U.S. Public Health Service, Bureau of Solid Waste Management, 1969.

16. Private communication with Dr. G. J. Trezek, University of California, Berkeley, December 12, 1975.

17. "Development of a Standardized Procedure for the Evaluation and Comparison of Size Reduction Equipment," Final Report, prepared by Midwest Research Institute for EPA under Contract No. 68-03-0137, January 23, 1973.

18. Savage, G., and G. J. Trezek, "On Grinder Wear in Refuse Communition," Compost Science-Journal of Waste Recycling, 15(4), September-October 1974.

19. Ruf, J. A., "Refuse Shredders," Waste Age, pp. 58-66, May/June 1974.

20. Private communication with Mr. J. Rivero, Union Carbide Corporation, Tonawanda, New York, December 10, 1975.

21. Private communication with Mr. Clem Finney, Occidental Petroleum Corporation, San Diego, California, December 10, 1975.

22. Private communication with Dr. Lyle Mudge, Battelle Northwest, Richland, Washington, October 17, 1975.

23. "Pyrolysis of Solid Waste: A Technical and Economic Assessment," Stanford Research Institute Report for West Virginia University, September 1972.

24. Private communication with Dr. Richard Bailie, University of West Virginia, Morgantown, October 31, 1975.

25. Private communication between Mr. Doug Fiscus of Midwest Research Institute and Mr. John Molitar of Union Electric, St. Louis, January 7, 1975.

26. Fiscus, D. E. et al., "Bottom Ash Generation in a Coal-Fired Power Plant When Refuse-Derived Supplementary Fuel is Used," presented at the ASME Solid Waste Processing Conference, Boston, Massachusetts, May 23-26, 1976.